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Programme de l'hydrogène
et du stockage
de l'énergie

Program Overview Hydrogen and Energy Storage: 1979 to 1985

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J.R.B. Murphy, and J.B. Taylor

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PROGRAM OVERVIEW

HYDROGEN AND ENERGY STORAGE

1979 to 1985

**J.E.A. Alderson, M. Hammerli,
J.R.B. Murphy & J.B. Taylor**

**National Research Council: Division of Energy
 Division of Chemistry**

October 1985

"WE SHALL NOT CEASE FROM EXPLORATION
AND THE END OF ALL OUR EXPLORING
WILL BE TO ARRIVE WHERE WE STARTED
AND KNOW THE PLACE FOR THE FIRST TIME"

T.S. Eliot

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EXECUTIVE SUMMARY

This overview of the Canadian Federal Hydrogen and Energy Storage program is essentially a review document covering the period from 1979 to 1985 during which the technical management of the program was the responsibility of the National Research Council of Canada.

The document presents various starting parameters which defined the program scope and the context within which the program was initiated. The mandates of the involved government departments and the data base, energy resource base, intellectual resource base, and industrial resource base available at that time are discussed.

A major factor determining the program content was the prediction that future availability of oil would decrease and that an increasing fraction of future Canadian energy supply would be produced in the form of electricity. It was recognized that utilization of energy storage and hydrogen systems could greatly facilitate this transition; that electrochemistry, the single most relevant scientific discipline, was not strongly represented in Canada; and that the utilization of these technologies could not be expected to have any large short-term impact.

The main strength of the industrial resource base for hydrogen related work lay in a Canadian water electrolyser manufacturing industry which had been supplying the international market for many years. In the energy storage area, particularly electric storage batteries, the Canadian presence was very limited.

The operating mode of the program was directive as opposed to responsive, however, program evolution was made with full recognition of Canadian initiatives external to the program, mainly in Ontario and Quebec. The program was supported by an Advisory Committee. Program activities were made public through requests for proposals issued through the Department of Supply and Services and by publication of an annual status report.

The overall objective was to ensure Canadian capability in the designated subject areas, and specific objectives were defined in four sub-program areas covering hydrogen production, hydrogen utilization, energy storage, and electrochemistry research. Strategies for attaining program objectives were tailored to specific circumstances with major influences being resource availability and known levels of research in other countries. A brief summary of the content and context of activities is included, and a full list of reports resulting from the work of this program is included in the appendices. One major role of the program was to provide inputs to

governments and regulating agencies with respect to the technological status and prospects of research activities. A continuing endeavour was to provide a focus and coordination of all related Canadian activities.

International activities under the IEA Hydrogen Agreement were strongly supported. These were considered to be most productive in giving Canadians access to, or knowledge of, foreign technical advances as well as benefitting the intellectual resource through technical meetings, workshops, and exchanges.

Significant events or milestones are listed to provide a brief chronological review of the program. Technical achievements of the program are presented in the context of significant international advances in the related technologies, and future developments and expectations for the Canadian projects are indicated.

Finally there is a brief discussion of the challenges and opportunities that have grown out of this program.

PROGRAM OVERVIEW
HYDROGEN AND ENERGY STORAGE
1979 - 1985

J.E.A. Alderson, M. Hammerli, J.R.B. Murphy and J.B. Taylor

1. INTRODUCTION

This document is planned to serve several needs.

Firstly, it summarizes what has passed by defining the context within which the program was conceived and by reviewing what was done.

Secondly, it provides references to individual expertise (the intellectual resource) and to written source material.

Finally, it reviews organizational and management aspects of the program, and identifies future technical challenges and opportunities.

The reader should be aware that the Hydrogen and Energy Storage Program addressed principally long term objectives so that its structure and content reflected this situation. Also, the abrupt termination of the program was not foreseen, with the result that the planned evolutionary flow of activities was not allowed to materialize and the accumulated intellectual resource rapidly dispersed. It is unlikely that this same resource could be reassembled should the need arise. It is considered highly probable that energy issues will again become dominant. Some would even attest to the inevitability of such a situation. Furthermore, there is a strong possibility that long before fossil hydrocarbon supplies become critical there will be a need to address environmental issues. These in all probability can only be solved by the substitution of alternative energy forms, particularly in regard to the resolution of carbon dioxide build-up in the atmosphere. Perhaps this document will enlighten and guide those who follow, by providing an easy access to the direction and content supported by the Hydrogen and Energy Storage Program.

2. STARTING PARAMETERS

Mandate

The Hydrogen and Energy Storage Program functioned within boundaries defined by two major mandates. The first of these was that of the funding agency, the Panel of Energy Research and Development (PERD), and the second was that of the operational agency, the National Research Council of Canada (NRC).

The mandate of PERD was essentially summarized in the Task Force Report of 1975 (1). The report recognised five general task activities of existing energy research and development, namely: Conservation, Fossil Fuels, Nuclear, Renewable Resources, and Energy Transportation and Transmission. Included within the 10 ongoing programs of the Conservation task was the Program of Energy Conversion, Storage and Hydrogen Systems which was later to become the Hydrogen and Energy Storage Program under the New Liquid Fuels task. In the National Energy Program of 1980 (2) it was indicated that the overall R&D emphasis should be shifted towards new priorities as stated below:

The three priorities for this increased effort are:

- Alternatives to gasoline. Canada has many fuel options. The challenge is to find the most promising, and provide the necessary support for commercialization, so that oil dependence can be quickly reduced in the transportation sector. R&D will give Canadians answers as to which options are technically feasible, environmentally acceptable, and economically viable.
- Increased efficiency of energy use, in all sectors of the economy.
- New energy sources ranging from coal - where technology must provide the key to environmentally safe use - to hydrogen, a promising option for future generations.

In 1982 the NEP Update (3) reaffirmed the central role of R&D and the above priorities. Relevant to this program was the following recognition given to hydrogen and electricity:

The Government of Ontario supports important research in alternative liquid fuels, with increasing emphasis on hydrogen developments. Electrical utilities in British Columbia, Saskatchewan, Ontario and Québec undertake major programs geared to improving efficiency in the generation, transmission, distribution and use of electricity.

In a specific response to The Report of the Special Committee on Alternative Energy and Oil Substitution to the Parliament of Canada (4) it said:

The Committee emphasized the potential of hydrogen, produced electrolytically from water, as a major future energy source for Canada. In 1982-83, the federal government will increase its expenditures on direct applied hydrogen research to \$5 million and this could double by 1984-85.

The most relevant aspects of the National Research Council mandate are defined in the following text taken from "The Urgent Investment, A Long Range Plan for the National Research Council of Canada" (5).

SCIENTIFIC AND INDUSTRIAL RESEARCH PROGRAM

Objective

- To create, acquire, and promote the application of scientific and engineering knowledge to meet Canadian needs for economic, regional and social development.

Sub-objectives

- To foster a milieu in Canada for the search for new scientific and technical knowledge.
- To promote, contribute to, and provide support for, a strong and viable scientific and engineering research and development capability in Canadian industry.
- To develop and maintain a capability to respond rapidly and effectively to forthcoming needs for scientific expertise, engineering know-how and in-depth analysis of problems in science and technology both nationally and internationally.
- To provide and maintain a capability to carry out major scientific and technological research and development programs to meet perceived national needs and priorities.
- To meet Canadian needs for major national facilities for science and engineering; standards and criteria.
- To contribute to meeting regional needs for research and development in science and technology in a coordinated and effective manner in co-operation with federal and provincial research organizations, universities and local industry.

The same document further discusses energy as a national economic issue in the following words:

The problem of exploiting Canada's vast sources of energy will continue to be an urgent national priority for the foreseeable future. Canada's need to achieve energy flexibility will require substantial investment in R&D in order to exploit options for alternate energy sources as the conventional oil and gas reserves dwindle.

An integrated R&D program of the federal government has been in place for a number of years under the general direction of the Minister of Energy, Mines and Resources. The program is planned, coordinated and monitored by the Interdepartmental Panel on Energy R&D. In the recent past, the Panel

has given highest priority to R&D projects directed to energy conservation and to increasing the supplies of oil and gas in the near term. These efforts will need to be continued throughout most of the 1980's. Research in support of nuclear energy will have to increase since more attention will be given to the disposal of radioactive wastes as well as to exploring the thorium fuel cycle and to establishing a nuclear fusion program.

NRC is a member of the panel, and is the lead agency for several elements of the national Energy R&D program. NRC will vigorously pursue its special role within the national energy R&D program by carrying out expanded activities in its areas of concern, for example: renewable energy, energy conservation in buildings, the development of energy-related data banks and related services and the evaluation of long term options for energy, such as fusion.

Hydrogen as a fuel, all forms of renewable energy and displacement of imported oil by development of Canada's coal and oil sands will each require substantial investment in R&D throughout the decade. Energy, the plan's third theme follows from these considerations.

Data Base

At the time when this program commenced all our currently existing hydrogen uses were already known; however, this did not include any use of hydrogen as an energy alternative. Technical information relating to this aspect was highly dispersed and scattered through the literature. Some of the more noteworthy reports and publications which were of relevance to the Hydrogen and Energy Storage program are listed below:

- "Energy Depot Program - Technical Feasibility Study" (6). Under this study by General Electric for the American military, ammonia was evaluated as an engine fuel with the objective of finding a fuel which would free the armed forces from reliance on hydrocarbon fuels. This study was the closest approach that could be found of a documented methodical fuel substitution.
- "A Hydrogen-Energy System" (7) explored technical aspects of the feasibility of an energy industry based upon hydrogen for energy storage. The source of hydrogen was anticipated as initially derived from natural gas and fossil fuels to be later displaced by hydrogen from renewable electric sources to be developed.
- The "International Journal of Hydrogen Energy" (8) is the official Journal of the International Association for Hydrogen Energy. It was first published in 1976 and remains the only international journal dedicated to hydrogen research and development.
- World Hydrogen Energy Conferences (9) were organized in association with the International Association for Hydrogen Energy. The initial

- conference (9) resulted from earlier hydrogen interests focused on environmental benefits expected to result from wide deployment of hydrogen as a fuel. Subsequent biennial conferences with published proceedings were held in Zurich, 1978 (10); Tokyo, 1980 (11); Pasadena, 1982 (12) and Toronto, 1984 (13).
- "Hydrogen As A Fuel" (14) was a report by the Hydrogen Panel of the Committee on Advanced Energy Storage Systems, done at the request of the Energy Storage Systems Division of the U.S. Department of Energy, who had been assigned responsibility for research and development on hydrogen. Suitable criteria for establishing the pace, timing, and technical content of appropriate research and development programs were requested, and examination of the status and problems of the principle hydrogen uses was considered to be a necessary concurrent development.
- "Proceedings of the Annual Contractors' Review Meetings" (15) were reports of work done under contract to the U.S. Department of Energy. Those proceedings dealing with Thermal and Chemical Storage and Electrochemical contracts were of particular relevance and provided a continual update of progress under parallel American programs.
- "Electricity/Oil Substitution" (16) showed that energy self-sufficiency through substitution of electricity for oil was a uniquely Canadian option, existing because of its energy resources having a large base of hydroelectricity and a proven nuclear capability. Natural gas was seen as available to smooth the transition, and substitution in the transportation sector was considered to be the technical limit to essentially complete conversion.
- "Energy Storage: A Review of Recent Literature" (17) described the technical and economic status of reversible energy storage methods with respect to Canadian needs.

Energy Resource Base and Projections

Two general directions were identified as leading toward the goals of energy self-sufficiency and dealing with a reduced availability of conventional oil. First, reduction of demand through conservation and increased efficiency of energy-usage, and second, by identification of alternative energies and fuels. Neither hydrogen nor energy storage provides any additional energy to our energy resources; however, the use of either can result in available energies being used more economically, with greater energy efficiency or with greater convenience. In this respect, as an energy vector, hydrogen is similar to electricity but with the advantage of being more easily stored. A first requirement for identifying opportunities by which hydrogen and energy storage might contribute to the

required goals was an assessment of the available primary energy resources with which it was to interface. Some pertinent facts and predictions are displayed in the following figures.

Figure 1 shows the primary energy mix in Canada since 1871, it demonstrates the extent of oil penetration and the penetration rates of changing energy sources. The form of these curves was apparently considered by many as inevitable, being relatively unperturbed by natural or contrived events. It must be realized that the earlier energy replacements here indicated arose from recognition of a better form of energy; they were not a consequence of reduced availability.

Figure 2 gives domestic demand and availability. Oil (1979-1990: low price scenario) is an example of the predicted domestic demand and availability of oil in Canada as forecast in 1976. Although the numerical values in such predictions were subject to great variability, the qualitative implications of these scenarios consistently showed large future shortfalls.

In Figure 3, the National Energy Program (1980) presented the estimated current division of energy consumption among the available resources, and a target energy matrix for the years 1990 and 2000. The target figures required an immediate expansion in the use of gas, and in the longer term an even greater expansion in the use of electricity.

Figures 4 and 5 show the availability of primary resource energy for the projected increased Canadian reliance on electricity. The increases were expected to come from renewable hydro electricity and/or from non-depletable nuclear generation depending on the regional availabilities of the former.

Figure 6 shows the breakdown of oil consumption by sector. Some sectors were more amenable to early replacement by natural gas or electricity than others. Because of its size the transportation sector offered the greatest potential for replacement but this was overshadowed by the greater technical difficulty and the more stringent requirements of a transportation fuel.

Figure 7 indicates the current and predicted hydrogen requirement of Canada. Due mainly to the large transportation fuel requirement a massive increase in hydrogen requirement was predicted, mainly to satisfy the needs of oil refining and synfuel production in addition to growth of non-energy uses. Referring back to previous figures, Canada was fortunate in having a choice of either electricity or natural gas as a primary energy resource for hydrogen production.

In summary, Canada was seen as an energy rich country with problems of energy form not quantity. Displacement of oil in the transportation sector was recognized as the most difficult substitution to make and the strategy in the short term was therefore to replace oil in other areas wherever possible and to save the available oil resource for transportation requirements.

It was also essential to see the Canadian situation within the broader context of the world energy problem. Of the many articles dealing with energy on an international scale we mention only "A Global and Long Range Picture of Energy Developments" by W. Hafele (18), which clearly indicated the global interdependence and the long time spans necessary to adjust to new energy sources. It also pointed to increasing environmental problems and potential geopolitical problems associated with the world distribution of resources. Within the more restricted boundary of individual national hydrogen activities Figures 8 and 9 are the graphic summaries from an IEA activity (19). These figures indicate the commonalities of current and future hydrogen production and hydrogen demand sectors. Of special significance to Canada was the comparison with the United States where hydrogen production trends were toward using residual fuel oil and coal as primary energy resource, compared to a trend toward electrolytic production in Canada. These divergent trends were expected to have implications particularly with regard to down-stream selection of suitable technologies for utilization.

Intellectual Resource Base

The single principal scientific discipline most relevant to the Hydrogen and Energy Storage Program was that concerned with electrochemistry and specifically that sub-group of electrochemistry describing energy applications as exemplified by electrolyzers, fuel cells, and secondary batteries. Immediately prior to the commencement of this program the Canadian activities had been summarized by Bélanger (25). The only significant federal activity in this area was a group headed by Casey in the Department of National Defence and located at Defence Research Establishment Ottawa (26). A large fraction of the limited amount of intellectual and research resource base was dispersed among numerous universities where it was tracked through the Natural Sciences and Engineering Research Council Strategic Grants funding activity. A list of those universities that had closest interaction with this program can be identified from the listing of Major Participants in Appendix D. Recognition of the deficiencies in this important area of Canadian activity led, in 1981, to a study for the establishment of an Electrochemical Technology Centre (27). The recommendations of this report, together with the conclusions of the Ontario government task force (28) were instrumental to the establishment of the Institute for

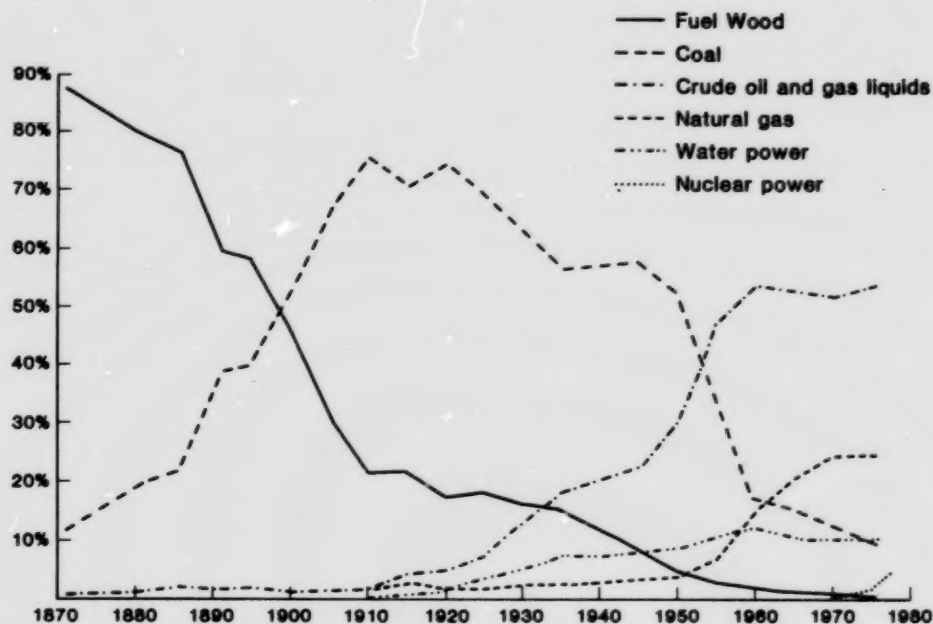


Figure 1. Primary energy mix in Canada since 1871 (after a figure in F.R. Steward, "Energy Consumption in Canada Since Confederation," *Energy Policy*, 6(3): September 1978 (20)).

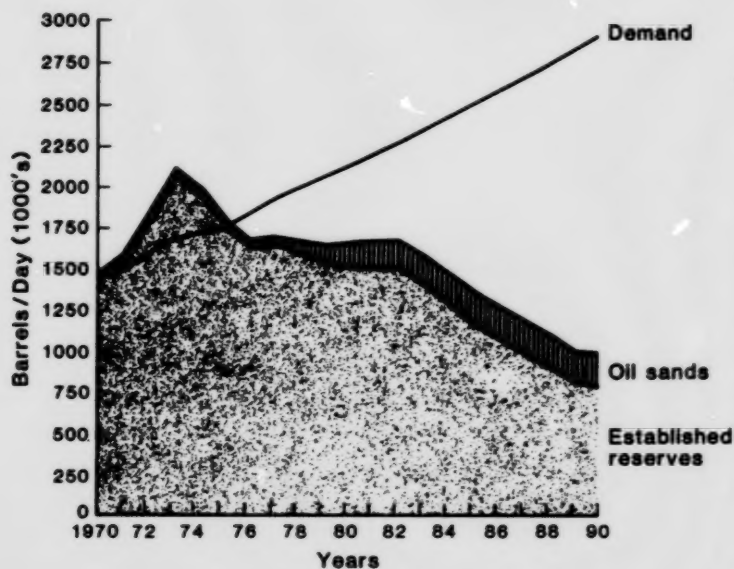


Figure 2. Domestic demand and availability: oil (1970-1990; low-price scenario) (after a figure in "An Energy Strategy for Canada - Summary," *Energy, Mines and Resources Canada*, Ottawa, Ont. 1981 (21)).

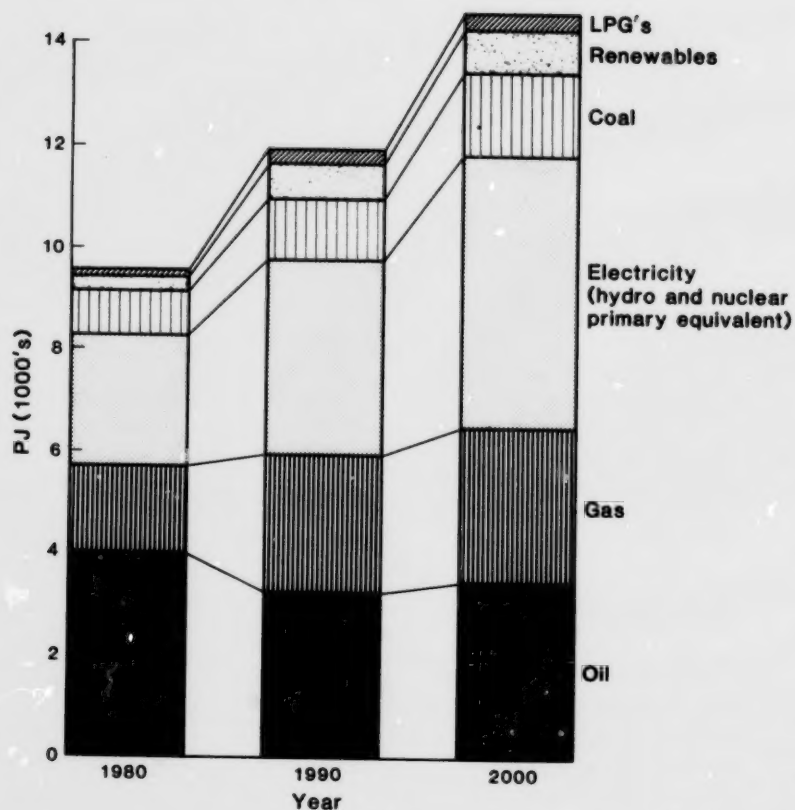


Figure 3. Energy source percentages (after a figure in "National Energy Program," Energy, Mines and Resources Canada, Ottawa, Ont. 1982 (2)).

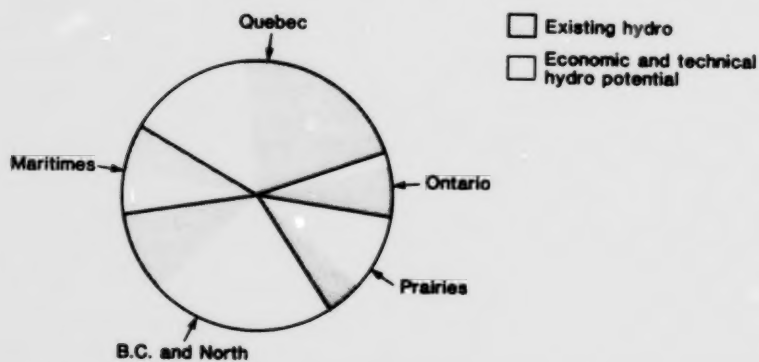


Figure 4. Hydroelectric resource base and potential (after a figure in "Canadian Energy Supply and Demand 1980-2000," National Energy Board, Ottawa, Ont. 1981 (22)).

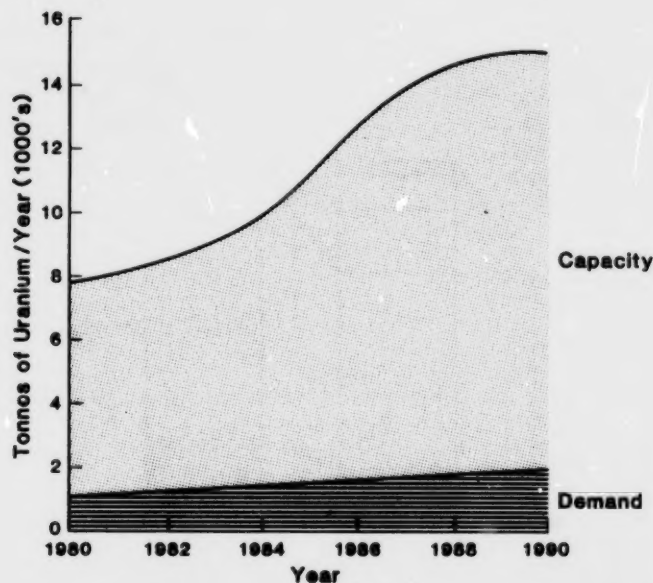


Figure 5. Nuclear energy resource base (after a figure in "Uranium in Canada, 1979 Assessment of Supply and Requirements," Energy, Mines and Resources Canada, Ottawa, Ont. 1980 (23)).

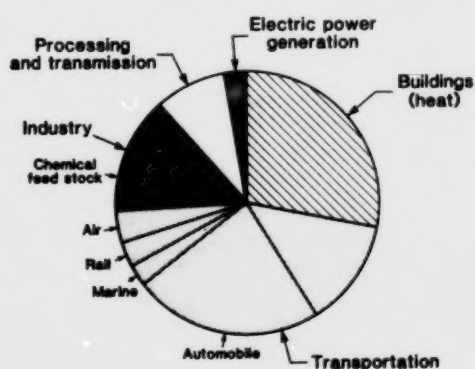


Figure 6. Oil consumption in Canada by sector (after a figure in "Canadian Energy Supply and Demand 1980-2000," National Energy Board, Ottawa, Ont. 1981 (22)).

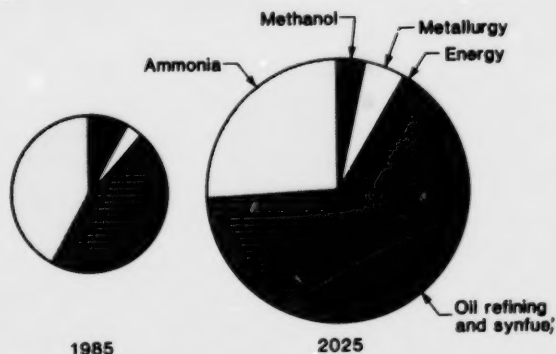


Figure 7. Projected hydrogen requirements of the Canadian economy (after a figure in J.B. Taylor, "Hydrogen Energy Prospects in Canada," Int. J. Hydrogen Energy, 1/2: 1984 (24)).

Hydrogen Systems (Toronto). This institute was formed under a cooperative action of the University of Toronto and the Government of Ontario (Ministry of Energy) with the expectation of significant federal funding. Its incorporation as recently as 1983 did not allow time for any significant effect on the Hydrogen and Energy Storage Program.

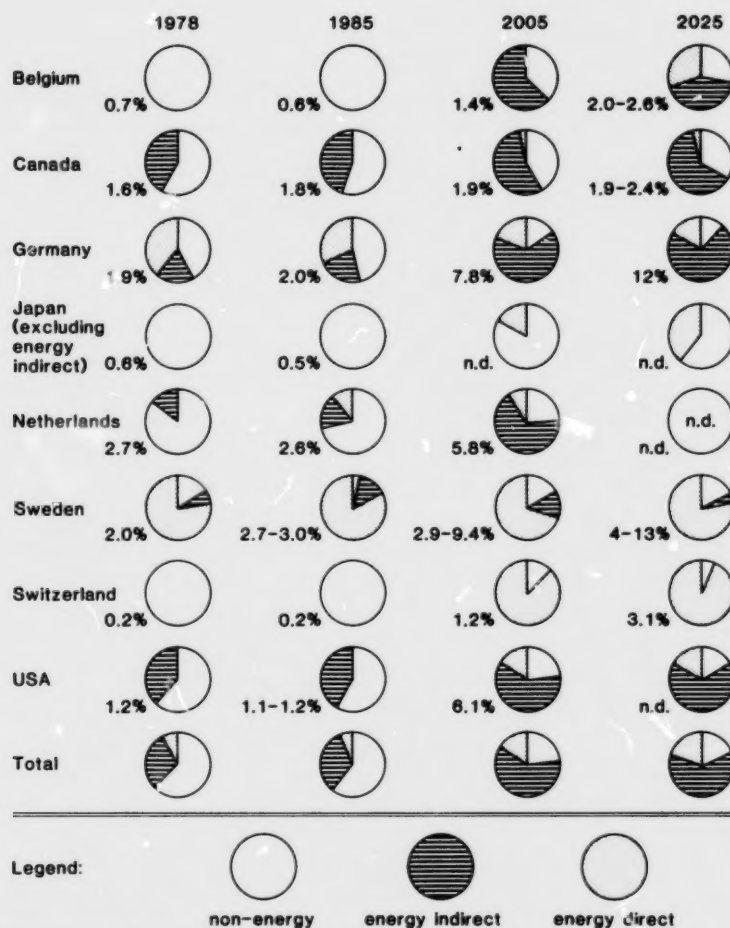


Figure 8. Development of shares of hydrogen demand sectors (after a figure in "Assessment of Potential Future Markets for the Production of Hydrogen from Water - Consolidated Final Report," IEA Program of Research and Development on the Production of Hydrogen from Water, Task III, 1980 (19)).

Industrial Resource Base

In April 1978 the final report of "Electrochemical Energy Storage Research Plan" was completed (29). Its objectives were: first, to assess Canadian capabilities; second, to identify problems in funding and administrative execution of the work and in the application of results; and, finally, to recommend a plan to meet Canadian research and development needs for 15 years.

Input was gathered from the battery manufacturing industry, raw materials suppliers, potential users of manufactured products, the academic

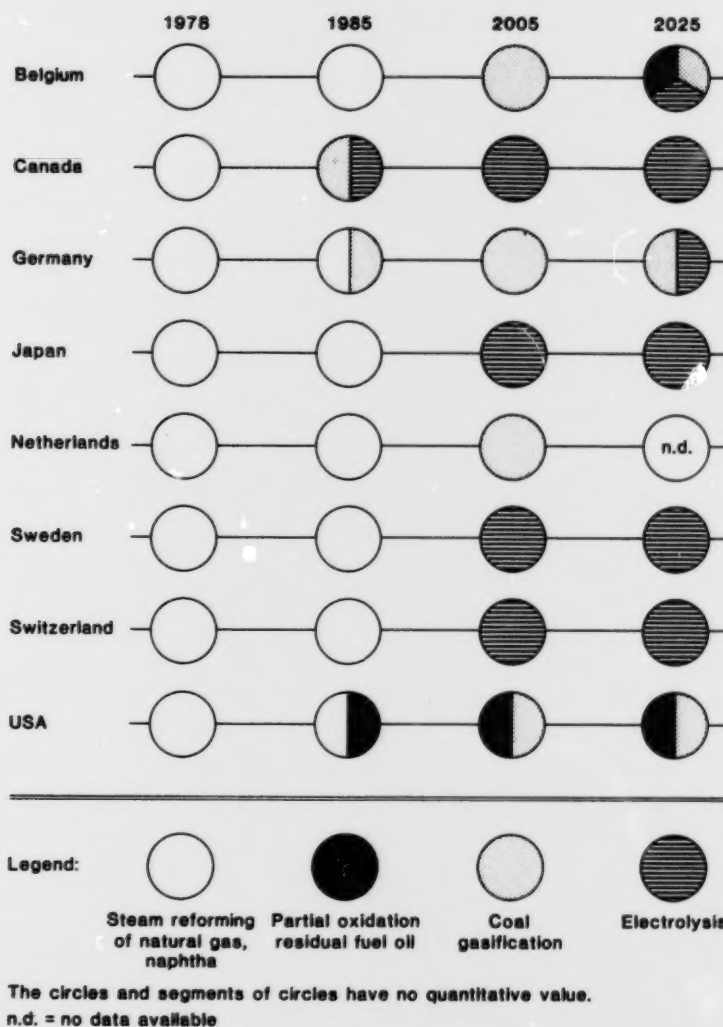


Figure 9. National trends in future hydrogen production (after a figure in "Assessment of Potential Future Markets for the Production of Hydrogen from Water — Consolidated Final Report," IEA Program of Research and Development on the Production of Hydrogen from Water, Task III, 1980 (19)).

community, and the American viewpoint as expressed by the Department of Energy. These inquiries showed that Canadian industry was undertaking only a small amount of research and development, mainly because of its access to foreign capabilities made available through its international affiliations. The highly competitive nature of the industry had encouraged independent development and hampered technology exchange. Utilization of government funding had proved unattractive to the industry because it was seen to endanger ownership and commercial secrecy and also because of the uncertainties associated with short-term government funding commitments. The prime requirement was seen as a need to coordinate the individual resources

into an effective mission-oriented team. The method of attaining this state was very vague. The major industrial resource of hydrogen production activity was solidly based in The Electrolyser Corporation Limited. An extract from their brochure follows:

The Electrolyser Corporation Limited is a Canadian company, well known in international markets as a manufacturer of electrolytic hydrogen plants, having supplied some 25% of such installations worldwide. TECL has produced close to 600 hydrogen plants which are operating in more than 80 countries on all continents, many of them for more than 20 years.

In 1980 Electrolyser Inc., a joint company of The Electrolyser Corporation Limited and Noranda Mines Limited, was formed to manufacture large industrial electrolytic hydrogen plants for the world market. The plants were to be based on the unipolar technology Stuart cell of The Electrolyser Corporation, modified under a joint development program.

Until recently the remaining elements of the hydrogen industrial resource base existed as independent dispersed industries, utilities, research institutions, and universities with a wide range of requirements and interests related to hydrogen. These have been brought together under the Hydrogen Industry Council which was formed in January 1982. The Hydrogen Industry Council Mission states:

The Hydrogen Industry Council fosters the development of hydrogen technologies and their use in industrial and consumer applications to the benefit of Canadian industry and the Canadian public.

As an industry-based organization, the Council aims to achieve these objectives by promoting the development of hydrogen-related industries and through the participation of Canada in international undertakings to advance hydrogen technologies.

The Hydrogen Industry Council has three major objectives.

First, to promote research and development in the areas of hydrogen production, storage, transport, and utilization.

The Council orients its programs towards maximum national economic benefit, and structures them so as to eliminate duplication through the greatest possible integration of efforts.

Second, to represent the hydrogen industry.

In this the Council acts as:

- a representative to governments to advise them on matters related to hydrogen research and development.
- a focal point for a continuing information exchange among members and with the international community.

- a representative to research organizations and national and international associations.
- a source of information for the general public.

The Council works with its members to establish policies and strategies relating to hydrogen and to ensure that members obtain sufficient resources to conduct their industrial research projects.

Finally, to seek out and promote hydrogen utilisation projects.

The ultimate objective of the Council is to increase and broaden the industrial use of hydrogen domestically and to promote the export of products, services and technology.

3. PROGRAM ORGANIZATION

The program was funded under the Panel of Energy Research and Development coordinated by the Ministry of Energy, Mines and Resources. Technical program management was the responsibility of the National Research Council of Canada and was undertaken as a joint activity of the Divisions of Energy and Chemistry. The accompanying organisational chart shows salient features of the management structure (Figure 10).

There were two levels of formal interdepartmental authority. At the executive and planning level was the Hydrogen and Energy Storage Committee which served to establish priorities and new technical directions. The ultimate authority for funding and overall policy and direction rested with a senior interdepartmental committee called the Panel on Energy Research and Development (PERD).

The Hydrogen and Energy Storage activity was one of the many sub-elements of the Energy Research and Development Program and was designated program 5.6. Each of the other sub-elements of the Energy R&D Program were the responsibility of specific government departments. Considerable liaison occurred between departments where inter-related activities were involved. Since there were numerous other routes for funding R&D in Canada, not all

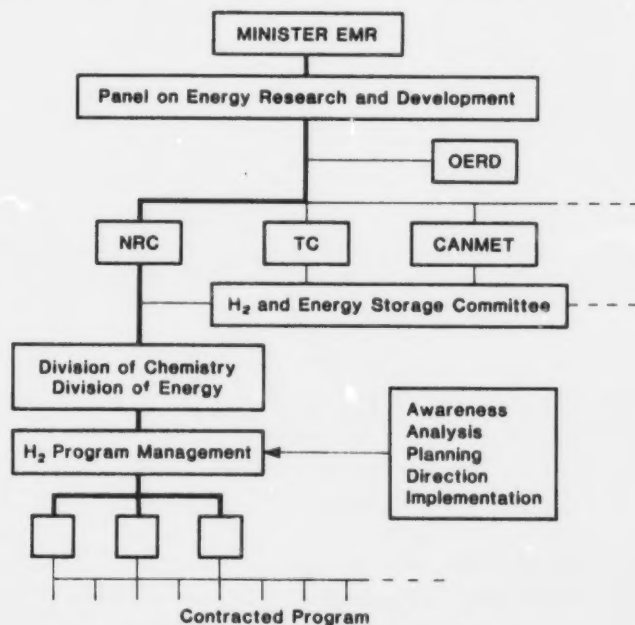


Figure 10. Program organization chart.

the relevant work was under the control of the Hydrogen and Energy Storage Program. Considerable liaison therefore was necessary with the funding agencies to avoid, as far as possible, fragmentation of effort, duplication, or conflict. This was largely done on an informal and cooperative basis.

It is further to be noted that the Hydrogen and Energy Storage Program was essentially a directed activity and was not a responsive or granting function. The program direction was of course not established in an arbitrary fashion and a great deal of consultation both inside and outside government departments occurred as an ongoing process. In this process the program was aided by the Associate Committee on Energy Conversion, Storage and Hydrogen Systems, whose members are listed in Appendix A.

The origin and terms of reference of this committee were as follows:

Canada is highly dependent on petroleum as an energy system. Inevitably, other energy sources must be substituted, and hence means of distribution and storage must be found. The National Research Council of Canada has been assigned responsibility for the program on Energy Conversion, Storage, and Hydrogen Systems, by the federal government's Interdepartmental Panel on Energy R/D. In August 1978, the Associate Committee was formed to advise NRC on this program.

Terms of Reference

1. To advise NRC and others as required by the Council, on the planning of technical needs, priorities, and implementation of the national R&D program on energy conversion, storage and hydrogen systems.
2. To advise NRC on the appropriateness of collaboration with other countries in energy conversion and storage programs.
3. To advise NRC as requested on other specific matters pertaining to the program on energy conversion, storage, and hydrogen systems.

Planned new activities under the program were announced in the Department of Supply and Services R&D Bulletin (30) on a regular basis. Bidders' lists were established and constantly updated. Requests for proposals were issued through the Department of Supply and Services and were subsequently evaluated by a team composed of appropriate experts in the field.

Accountability for the program was the direct responsibility of the program managers and strong emphasis was placed on regular and detailed technical reviews and written reports. Some of these reports may be available through the lending services of the National Science Library (CISTI). Commercial confidentiality of certain activities precluded the general distribution of

some reports. However, a condensed report was issued each year in both official languages by the National Research Council and was available to anyone upon request (31, 32).

This program, within the context of other Canadian federal energy activities, is further described in "1983 Guide to Research and Development Activities Resulting from the National Energy Program of the Government of Canada" (33).

4. PROGRAM OBJECTIVES

During the peak period of activity immediately prior to November 1984, the Hydrogen and Energy Storage Program was comprised of the four subprograms that are listed below together with their respective objectives.

Hydrogen Production

To ensure that Canada has the technical and engineering capability to produce the lowest cost hydrogen from indigenous resources.

Specific objectives include:

- Development of materials, components, and techniques for advanced electrolyzers.
- Maintaining awareness of world trends in hydrogen production alternatives.
- Support of industrial development to capitalize on the results of research.

Hydrogen Utilization

To assess and develop techniques related to the effective use of hydrogen as an energy carrier in Canada.

Specific objectives include:

- Assessment and development of appropriate methods for hydrogen storage and distribution.
- Development of a data base and engineering capability in hydrogen end-use and energy conversion including heat engines and fuel cells.
- To review, analyse, develop and disseminate information enabling the safe use of hydrogen.

Energy Storage

To identify and develop economic and practical energy storage technologies to be applied to the displacement of existing hydrocarbon fuel systems by new and inexhaustible energy sources.

Specific objectives include:

- Assessment and development of electric batteries appropriate to Canadian needs in mobile and stationary applications.
- Development of flywheels for high power density components of hybrid vehicle power units.
- Assessment and development of electric vehicle systems and components appropriate to Canadian requirements.
- Development of thermal storage for residential and industrial applications. (Responsibility for low temperature storage appropriate for solar applications was assigned to the Solar Energy Program.)

Research in Electrochemistry

To establish and provide operating support of an institute to perform and coordinate applied electrochemistry and electrochemical engineering for energy applications.

This sub-program was derived from the recommendations of the Associate Committee on Energy Conversion, Storage and Hydrogen Systems, March 31, 1981, which were as follows:

An Electrochemical Technology Centre must be established immediately.

The activities of the Centre will include R&D on advanced electrolyzers for the production of hydrogen; fuel cells; storage batteries; electrometallurgical processes; and all electrochemical processes currently recognized and yet to be realized which can contribute to the Canadian energy matrix.

We recommend that this Centre be established as an Independent Corporation such as a Crown Corporation or a subsidiary of an existing Crown Corporation.

This corporation must be established by the Federal government and financed with public funds.

In view of its responsibility for the Federal program on energy conversion, storage and hydrogen systems, the National Research Council must maintain a direct and continuing involvement in the programs and direction of the corporation.

Further, the Committee added the comment that:

In the event that overtures are received which impinge directly on these recommendations and on energy related research and development in electrochemistry and electrochemical technology, the Federal response must be positive. In the ensuing negotiations, the National Research Council must

press not only for a major Federal presence in direction and management of the program, but must resist any mandate which will fragment the national program in electrochemical research.

Many of these objectives were not immediately realizable for one reason or another. The Electrochemistry Institute, for example, required commitment of capital funds and person years. Other sub-programs such as those involving advanced batteries and electric vehicles were component oriented and therefore depended for their ultimate success on a coalescence with emerging technologies from elsewhere. Above all, the program funding levels were simply too low, and the R&D mandate too restrictive, to carry any of the technologies to full commercialization. To do this required private sector investment. In some cost-shared arrangements this process worked well. In other work such as the heat storage electric furnace for domestic space heating, the industry saw no incentive in proceeding because acceptance of the technology depended on regulating action to create time-of-day electric rates. No assurance could be obtained that Canadian utilities were about to introduce such peak load shedding incentives.

In the course of the program it became increasingly apparent that government intervention would likely be needed to bring many alternative technologies to the market place. This results simply from the fact that the energy market place is already controlled, e.g., subsidies on diesel fuel supplied to Northern communities, as well as negative taxation and other incentive programs to encourage attainment of specific objectives. One principal role of the program was then seen as providing input to governments and regulating agencies with regard to technological status, viability, costs, performance characteristics, etc.

5. STRATEGY

In developing any program plan there are always constraints. The resources available to execute the plan must therefore be identified and their magnitude quantified or defined in some way. The principal resources needed to execute an R&D program to achieve the aforementioned objectives are fiscal and intellectual. In general, the capacity to accelerate the development of the intellectual resource is not dependent on the available funding. This was usually the case at the time of the work undertaken in the Hydrogen and Energy Storage program. The existing intellectual resource base or capability was in most cases less than would have been desired. The program planners were therefore faced with the need to define a course which would optimize the use of assigned funding, maximise the use of all resources, provide some tangible near-to-mid-term benefits, and contribute to an evolution of expertise which would have lasting value and produce longer term benefits on many fronts.

The options considered were as follows:

- (i) Merge and focus existing expertise to address newly defined problems.
- (ii) Develop new expertise perceived to be necessary to address present and possible future problems.
- (iii) Draw on foreign technology and existing capabilities outside Canada.
- (iv) Identify pivotal technologies and concentrate maximal resources in a blitz approach.
- (v) Involve industry and all levels of government to identify common objectives and pool resources.

In fact the strategy adopted was to utilize all the options cited here. Effective communications channels were developed with all sectors. The program was, however, never a responsive or granting function since this activity was handled elsewhere in NRC and in other agencies. In spite of this, the program direction did avoid the proponent approach where "winner" technologies are encouraged to the exclusion of all else. A consensus approach was sought and achieved. The formation of industry groups such as the Hydrogen Industry Council made eminent sense and was encouraged.

In sharp contrast, communication with the scientific community is a well-established process involving the publication of material in the open

literature and the holding of conferences and symposia. All these channels were pursued. A significant challenge stemmed from the interdisciplinary nature of the subject material of principal interest to the program. Many journals and technical meetings are highly specialized so that new forums had to be explored.

The holding of the 5th World Hydrogen Energy Conference in Toronto in 1984 was a very successful interdisciplinary event with worldwide participation. It brought many benefits to the program and to Canada.

One of the strong themes of the program was the international involvements through the IEA Hydrogen Agreement. The efforts and commitments made in regard to this agreement brought extremely beneficial rewards to Canada. The technical meetings, workshops, and exchanges benefitted the development of our intellectual resources in a way which simply could not have been duplicated in any other process. In addition, Canada gained access to, or knowledge of, new technologies and at the same time enjoyed something of a storefront exposure for its own, often more modest, technological achievements.

Although the proponent approach has been decried, there were several instances in which the program management believed it to be beneficial to identify and address pivotal technologies. An example of this occurred with the Li/FeS battery. This high temperature system employs a molten salt electrolyte and had been under investigation around the world for many years, so long in fact that all original patents had expired. Recent work in the United States had brought the battery close to a viable commercial technology in all but the cost area. The reason for this was that it had been found to work best with a boron nitride separator which was supplied at extremely high price by a single American manufacturer. Recognizing the pivotal nature of this technology, NRC moved to assimilate American battery technology whilst at the same time supporting the development of a new process to make boron nitride felt separator material at very low cost. The gambit worked and put a Canadian commercial developer at the forefront of world technology in advanced batteries.

One caution must always be observed in formulating strategy, yet it was seen to be ignored time and time again by those writing reviews, analyses and providing advice of a consultative nature. This concerns the rigid application of economic criteria to defining project priorities. In general, with emerging technologies such economic data are not reliable. Unfortunately, it usually requires a sophisticated level of expertise to detect the flaws in the arguments. On this account, it was only very rarely that economics criteria were used in making program choices. The initial research phase was concentrated on technical proof-of-concept, and

economic aspects at this stage were relatively unimportant. If a project survived to subsequent stages of development, then economic considerations played an increasing role and the scientific research was increasingly directed toward cost reduction through replacement of expensive materials and processes by less costly alternatives. . The time frame for this progression was variable. Activities under the Hydrogen and Energy Storage program reached various stages of development as a result of different start times and different levels of development at the time of commencement. The most advanced activity was that in support of advanced electrolytic hydrogen production technology which had received considerable attention prior to the commencement of this program, and which consequently had the most clearly defined economic prospects. The acceptance of this technology in a business venture at Bécancour Quebec strongly supports the claim that there are circumstances under which this hydrogen production technology can be competitive with more conventional methods. In all areas of the program examples can be found which show the susceptibility of projected costs to exaggeration depending on the interests of the author. It was an objective of this federal program to maintain as far as possible an unbiased evaluation capability with respect to such claims. In fact, in many cases one purpose of undertaking the work was to provide reliable and meaningful cost information.

As has already been mentioned in Section 2 on starting parameters, the program scope was narrowed by considering only the displacement of oil by electricity. This strategy was based on the knowledge that many opportunities exist for expanding the electrical resource base. Many new energy forms will undoubtedly reach the marketplace in the form of electricity. The strategy was therefore to address the task of interfacing electricity with future energy markets which are now principally served with oil.

6. PROGRAM CONTENT

This chapter presents a concise description of the technical scope of the program together with the rationale that led to decisions on program focus and the limits of program coverage. A more detailed account of the individual activities can be found in the Status Reports of the Hydrogen and Energy Storage Program, 1982 to 1985 (31, 32).

Hydrogen Production

Water Electrolysis

Water electrolysis was seen as the most viable method for hydrogen production in Canada that was independent of fossil fuel primary resources. This was based on the large existing and potential energy resources in the form of hydraulic and nuclear electric generating capacity. It was recognised that the first step toward the extensive use of hydrogen as an energy commodity was the development of a large-scale efficient production technology. Accordingly, the largest fraction of resources in the hydrogen production sub-program was committed to research and development of water and water vapour electrolysis. The initial thrust of the water electrolysis program was through existing Canadian Technology which was already being marketed on a world-wide basis. A program for upgrading this technology, supported by federal funding through the Department of Industry, Trade and Commerce, had already commenced in 1976. It was recognised that without substantial improvement, this technology could not remain competitive in the world market. More specifically, it would not be competitive for the predicted multimegawatt plant sizes because the conventional equipment was too small and did not lend itself to direct scaling.

At the completion of the above-mentioned Industry, Trade and Commerce program in 1983, a 0.6-MW pilot plant consisting of three 100 000 Ah electrolysis cells was operating at the research department of Hydro-Québec (IREQ), Varennes, Quebec. The Hydrogen and Energy Storage Program continued to support this development of Canadian unipolar water electrolysis on a cost-shared basis. Over a period of two and a half years these cells were refurbished with components of new design and advanced materials. Two additional cells had been installed resulting in a total capacity of 1.0 MW. The experience gained from operation of this experimental plant allowed the new company, Electrolyser Inc., to design a 7-MW electrolytic hydrogen plant for the Bécancour Project where electrolytic hydrogen and byproduct hydrogen from a chlor-alkali plant will be used as feed for the production of merchant liquid hydrogen.

With the help of Atomic Energy of Canada Limited, research and development on a new process for the economic recovery of heavy water, as a byproduct

of the electrolysis process, was conducted in association with the above program of improvement to existing electrolyser technology. Justification for this activity was based on a market study forecasting an increase in sales of water electrolyzers in countries requiring heavy water for nuclear programs. Known as the Combined Electrolysis Catalytic Exchange (CECE) process, the world licencing rights are owned by Electrolyser Inc. who successfully demonstrated this process on a modest scale.

An alternative approach to the introduction of hydrogen as an energy commodity was through dispersed production units capable of interfacing with various remote renewable energy supplies. A hydrogen production technology suited to this concept was expected to be significantly different to that described above requiring relatively small, stand-alone, inexpensive, and low maintenance systems. The Static Water Feed Electrolysis System under development for space applications was considered to be a promising starting point for such a system. However, in-house testing and evaluation showed that the concept development at that time was not sufficiently advanced, considerable cost reduction of the system would be necessary, and it was concluded that the system should be reexamined at a later date.

Research and development of materials and components of special significance to advanced water electrolyzers was carried out in parallel with the above system developments. The anticipated application of this work was not necessarily confined to the Canadian unipolar technology. From fundamental considerations it was known that an increase in operating temperature would be advantageous to the efficiency of electrolyser operation. The restrictions on practical operating temperatures were imposed by the durability of materials in the harsh electrolyser cell environment.

One of the key components for improvement was the separator which has traditionally been made of high grade asbestos with a maximum operating temperature of 90°C. Above this limit, chemical degradation takes place at a rate unacceptable for a life time of approximately 20 years which is expected from commercial electrolyzers. Several approaches were taken to finding a suitable substitute for asbestos. The high electrical resistance of hydrophobic plastic materials was successfully decreased by surface treatment to make them hydrophylic. This condition in all cases was found to be only temporary and the line of research was discontinued. New plastic separator materials that were inert to strong alkaline solution were prepared by modification of existing polymers; however, they could not compete with asbestos for either cost or chemical stability. A third approach for preparing improved high temperature separator material was from selected monomers whose polymers could be expected to have the required properties. The selected polymers, called aromatic ionomers, had the

additional advantage of also being suitable as solid polymer electrolytes. Characterization of mechanical and electrochemical properties indicated chemical stability up to 180°C without significant degradation. These aromatic ionomers could be cast with very small holes, making them suitable as separators, or without the holes in a form suitable for a solid polymer electrolyte. At the completion of the program, sheets of 20 cm x 30 cm had been cast and long term tests under water electrolysis conditions had been commenced. The project was transferred successfully to the Department of Energy, Mines and Resources.

The second major electrolyser components to benefit from upgrading were the electrodes. Efficiency of reaction at the electrodes is predominantly a question of electrocatalysis, especially when high current densities are required. Electrocatalysts were studied for both the hydrogen and the oxygen evolution reactions. New materials developed for the former were not able to match those developed in-house by Noranda, but remain a reserve option. Many materials of the perovskite and spinel type were screened for suitability at the oxygen electrode. The preferred compounds were successfully bonded to metallic screens and are currently being tested at the Noranda Research Centre and in Belgium under the IEA Hydrogen Program. Long-term tests are required before this material would be acceptable for commercial use. Although preliminary results suggested an inferior performance to other alternatives at low temperatures, at higher temperatures the activity increased and seemed to improve as a function of time.

An ion implantation technique was investigated for controlled placement of noble metal catalyst ions which would have reduced the noble metal requirement. However, insufficient improvement was obtainable to justify continuation of these experiments. A low-level fundamental effort supporting investigation of multi-electron transfer electrocatalysts for the oxygen evolution reaction had recently been commenced but was not in operation long enough to have reached any conclusions.

Photo Production of Hydrogen

Photo production of hydrogen refers to the direct production of hydrogen from absorption of sunlight in water, generally at an electrode interface. Over the period of this program there were considerable advances made in this field throughout the world, but these were all in the nature of basic laboratory experimental observations and no large-scale prototype has ever been attempted. A basic problem in utilizing energy from such dispersed sources is the requirement of extremely large collection areas and the unit costs must therefore be very low to produce a system that is competitive with those that take advantage of natural concentrating mechanisms.

Because this was not considered to be a high priority Canadian option there was very little activity funded directly from the Hydrogen and Energy Storage Program. However, contact was maintained with advances and activities in this field through work at EMR (CANMET). Here, in-house research was conducted on the study of electrode materials which provided the contact for Canada in the IEA Task VI activities, and also provided a focus for activities at Canadian universities which were mainly supported by NSERC strategic grants.

Thermal Production of Hydrogen

Thermal production of hydrogen refers to the use of thermal energy to produce hydrogen from water. It was seen as an alternative to fossil-fuel-based hydrogen production for countries where electricity costs prohibit the use of electrolysis. The temperature of the heat required for direct thermal splitting is extremely high but can be reduced, at the cost of greater process complexity, by the introduction of multiple cascaded thermochemical cycles. It was anticipated that the primary heat source for this process would be solar concentrators or high temperature nuclear reactors. Because neither of these thermal sources was available or planned in Canada, the Hydrogen and Energy Storage Program supported only an awareness, reporting, and analysis of international activity in this area. This support included a relatively low level investigation relating to common problems of the more successful systems in order to maintain credibility and access to international activities. It has been estimated that the cost of hydrogen from some thermochemical production cycles could be competitive with water electrolysis, particularly where the cost of electricity is high and the appropriate high temperature heat sources are available.

Hydrogen Utilization

Fuel Cells

When the Hydrogen and Energy Storage Program commenced there were several fuel cell companies in the United States and other activities scattered around the world, but very little activity of any kind in Canada. Even now there is no production unit available for terrestrial applications. As a late starter with limited resources the options for Canadian participation were restricted. The first objective of the Canadian program was to obtain "hands-on" experience with existing technology in order to educate potential users and to acquire sufficient expertise for recognising specific Canadian needs and opportunities. A prototype 40-kW phosphoric acid fuel cell power plant designed for stationary applications was purchased from United Technologies, U.S.A. A program of testing was designed around this

unit, which is a potential replacement for diesel generation in remote locations and has potential in a cogeneration situation where the waste heat can be utilized. The B.C. Hydro and Power Authority was awarded the contract for its placement on a mobile test bed and for the initial site test project. This program is tied into an American program run by the Gas Research Institute and through this association provides access to results from about 40 other test programs. It had been the intention of the Hydrogen and Energy Storage Program to support Canadian testing of other fuel cells such as the high temperature ceramic electrolyte cells and the European alkaline fuel cells. Because fuel cells are effectively electrolyzers in reverse it is not surprising that many of the materials developed as electrolyzer components also have potential applications in fuel cells. This is exemplified by the in-house work carried out at CANMET on a ceramic-electrolyte-based fuel cell, and in the solid polymer electrolyte fuel cell work sponsored by Defence Research Establishment Ottawa/Department of National Defence (DREO/DND). These material developments were viewed as very promising entry points for a Canadian fuel cell activity and were made even more attractive by the possibility of spin-off products and applications.

Engines

Heat engines offered a time-proven method for converting energy stored in a fuel into useful mechanical energy. All engines are to some extent limited in efficiency of operation by the fundamental thermodynamic characteristics of the operating cycle to which they were designed (e.g., Diesel, Otto, and Rankine cycles). This makes them, at first glance, less attractive than the fuel cell - electric motor combination. However, engines are highly developed and inexpensive, and major recent advances in cycle topping and bottoming concepts are providing dramatically increased efficiencies. These factors, together with the potential efficiency benefits associated with the combustion of a non-hydrocarbon fuel such as hydrogen, indicated that engines could not be ignored as future energy conversion devices.

A considerable amount of early effort in several countries had been expended in adapting existing gasoline engines to run on hydrogen fuel for demonstrations. These engines coped with hydrogen, but did not exploit hydrogen's beneficial characteristics. More recently, in Canada and elsewhere, projects were commenced to determine how good engine design could utilize unique aspects of hydrogen combustion to achieve more efficient energy conversion. Emphasis was placed on direct injection, optimized combustion chambers, and high compression ratio to achieve higher power, high efficiency, and reduced nitrogen oxide emissions. The Canadian activities were undertaken in university and NRC laboratories in a coordinated program. The commencement of these new approaches was too recent for them to have produced significant technical results.

Another project of the Hydrogen and Energy Storage Program was designed to assess how gas turbine combustors could be optimized to take advantage of hydrogen's characteristics. Little work had previously been done in this area, in spite of strong international interest in long-range aircraft applications. An initial study identified several advantages from hydrogen fueling these gas turbine engines which also have marine, rail, and stationary applications.

A major drawback of hydrogen, particularly for mobile applications, is the difficulty of storing it in either its liquid, gaseous or metal hydride form. An attractive alternative was a liquid carrier such as ammonia or methanol. Some efforts were therefore devoted to an assessment of the use of liquid carriers for hydrogen storage and energy conversion. From the standpoint of application to engines, the two major areas of focus were

- dissociation of methanol on-board the vehicle
- development of experimental ammonia-fueled engine technology

In addition to the convenience of a high energy density liquid fuel, the use of engine exhaust heat to dissociate methanol (into hydrogen and carbon monoxide) before combustion in the engine was attractive because of the predicted efficiency gains. Initial contract work suggested that the concept was worth pursuing. The National Research Council's plan was to combine American and Canadian expertise in a carefully designed program to determine whether or not cost-effective efficiency gains could be achieved in practice. This work program was not completed and the opportunity to share in this definitive work was lost when the Hydrogen and Energy Storage Program was terminated.

Because ammonia contains only nitrogen and hydrogen it can be synthesized from air and water. The U.S. Army recognized its potential as an engine fuel (produced from transportable nuclear reactors) in the early 1960's. Under this "Energy Depot" concept, the U.S. Army successfully converted several engines to run efficiently on ammonia. Efficiencies achieved were higher than with hydrocarbon fuels, as predicted theoretically, but no work was done to optimize the engine. The work at NRC was aimed at determining how a diesel-type engine could be optimized to take advantage of ammonia's characteristics. The work showed that high power, higher efficiencies than with hydrocarbons, and low emissions (including residual ammonia) could be achieved without the need for combustion-enhancing additives if careful attention was paid to combustion chamber configuration and to ignition timing and spark energy.

All of NRC's engine work had the objective of adding to the data base required for future hydrogen energy conversion decisions, including those related to relatively near-term niches for hydrogen utilization. For example, the ammonia work was associated with possible near-term applications for storage and conversion of energy from remote renewable resources. The NRC work was closely coordinated with complementary German and Japanese work under the IEA cooperative program of projects called "Hydrogen Storage, Safety and Conversion," which was established in 1983 (see later under "Safety").

Hydrogen Storage

Hydrogen storage is a specialized class of energy storage and many of the considerations of energy storage in general are also applicable to hydrogen storage. Energy storage is deployed to smooth energy flows across the interface between variable rates of production and demand. In the past, an increasing amount of energy storage requirements was being met by the use of oil in its role as an energy storage medium. No single storage technique is expected to be able to optimally satisfy all storage requirements, and few can match the convenience and performance characteristics of oil even in single specific application areas. Similarly, no single hydrogen storage technique is most suitable for all hydrogen storage requirements, and for any single application there is a choice of several storage techniques available. Various characteristics of the different storage technologies, such as storage density, rates of delivery, etc., were required to assess their suitability for specific applications. A related activity was the understanding of the basic science involved in these technologies and the degree to which these characteristics could be modified to adapt a particular storage technique to a specific application.

At a fundamental level, work was supported on metal hydride storage, which generally has very attractive features from a safety point of view. Various shortcomings with respect to specific applications have prevented widespread utilization. Programs of research on basic mechanisms and the manipulation of hydride properties had been supported in many countries and some non-storage applications in hydrogen compression, hydrogen pumping, and heat pumping are now approaching commercial status. A relatively new concept for hydrogen storage, referred to as microencapsulation, was evaluated under this program. Microencapsulation as a storage mode involves high pressure hydrogen charge and discharge of glass microcapsules. This is made possible by the temperature dependence of hydrogen diffusion characteristics and the high tensile strengths of certain glass materials. Many of the limitations of this concept were identified and changed by variation of capsule parameters. The final indications were that in all areas of hydrogen storage where this concept might be used there were other

techniques more suitable. The possibility of applications relating to hydrogen gas separation or purification remained to be assessed.

Because in the past the majority of hydrogen for large-scale demands has been produced as required from natural gas, the storage of hydrogen in practice was effectively reduced to storage of the natural gas. With future hydrogen production by large-scale electrolysis new storage options may be preferred. Bulk hydrogen storage in the gaseous state in above-ground pressure vessels or underground in rock caverns, salt domes, or permeable rock formations was explored under this program, as well as bulk storage as a liquid in cryogenic containers. The availability of specific Canadian sites was established. By linking these to potential users, a set of plausible scenarios was created from which an appreciation of site specific problems, advantages, and economics was obtained. A major conclusion was that each potential deployment of bulk hydrogen storage had to be considered on a case-by-case basis to determine the optimum storage method. The possibility of converting electrolytic hydrogen to a hydrogen-rich chemical compound capable of storage by conventional methods was considered separately under the program element "Liquid Hydrogen-Carriers." This was seen as particularly attractive for near term, high energy density, transportation fuels.

Safety aspects of hydrogen storage technologies were considered of prime importance. A major safety problem was found to be associated with hydrogen embrittlement of metals. Within this program, hydrogen safety aspects were studied in relation to specific storage methods and also more generally under a separate program element of "Hydrogen Safety."

Safety

Recent increased emphasis on hydrogen utilization led to an expectation that there would be a growing number of new "users" (especially, initially, the R&D performers in the university and industrial sectors) who would be faced with using hydrogen safely in laboratory experiments and pilot applications. There was a recognized need for a coherent hydrogen safety data base accessible to such users. It was also realized that NRC required expert advice in this field, regarding the structuring of NRC's hydrogen safety R&D program, the acquisition and dissemination of appropriate information, and the identification of shortcomings in regulations, codes, and standards.

The NRC responded to these needs in two ways. First, starting in 1992, a number of contracts were let with a view to gathering data about such topics as the safety problems associated with the use of hydrogen as a ground

transportation fuel, problems with materials used for hydrogen containment, and the impact of hazardous conditions on the design and performance of liquid hydrogen tanks for ground transportation (this latter was a cooperative project with the governments of Ontario and West Germany). Second, in 1983 NRC set up a small task group on hydrogen safety which led to the establishment, in mid-1984, of a Hydrogen Safety Committee whose terms of reference were to provide advice on hydrogen safety to NRC. The committee members were drawn from the private sector across Canada. During its initial year the committee members were active in many areas which included analysis of the status of codes, standards, and regulations applicable to hydrogen safety and assessments of how to deal with negative public perceptions of hydrogen safety. The committee also organized workshops on hydrogen safety at the Fifth World Hydrogen Energy Conference in 1984 and at the Second Canadian Hydrogen Workshop in 1985.

As NRC's interest in hydrogen utilization grew, so also did that of a number of member countries in the International Energy Agency. This led to the establishment, in 1983, of a new program of cooperative projects called "Hydrogen Storage, Safety and Conversion." Canada is a participant in this program, together with Japan, Germany, Sweden, Switzerland, and the United States. The activities of NRC in the field of hydrogen safety were contributed to this IEA program. The international concern about hydrogen safety was strong and there appeared to be particularly keen interest in the initiatives taken by NRC in this field.

Hydrogen Systems Analysis

Hydrogen systems analysis activities were primarily carried out as an aid to program planning, decision making, and setting of priorities. The financial resources of the program were not sufficient for it to engage in system demonstrations. System studies were necessary to identify critical components or requirements of both technical and non-technical nature that might favour or impede future commercialization. The identified factors became part of the program input required to structure the program for maximum effectiveness. System concepts were continually acquired through the program personnel interactions with experts outside the program, or through the technical literature. Detailed technical economic system studies could not be carried out in-house because there was insufficient personnel available and because of the government contracting-out policy. A particular emphasis of these studies was to identify specific Canadian opportunities and problems. A major recent study was to identify, document, and analyze possible new uses of hydrogen in Canada, giving special consideration to those applications that would benefit from a future increased Canadian capability in electrolytic hydrogen production. The research problems to be overcome before such applications could be demonstrated were to be considered in establishing future program priorities.

and timing. Considerable attention was given to ensuring that the contractor assimilated information from the widest possible range of potential users and that specific Canadian cases were comprehensively documented. It is anticipated that some elements of this activity will be continued under the auspices of the Hydrogen Industry Council.

System studies, covering a more specialized and restricted scope of interest, were included under related program elements.

Energy Storage

Advanced Batteries

At the time when this program was begun, the Canadian battery industry was almost entirely composed of branch plant operations based on technologies developed in foreign countries. Available federal government expertise in this area was confined to a single electrochemistry group at Defence Research Establishment Ottawa, who were called upon to provide technical direction for energy funded activities. Under this mode of operation a variety of small projects was supported. With subsequently increased funding and technical capability, later electrochemical activities were directly managed from the Hydrogen and Energy Storage Program.

The future predominant use of rechargeable batteries in Canada was believed to be for traction purposes. Load levelling activities promoted in other countries could be performed in Canada more economically by other means. To carry out a meaningful program with the funding available it was necessary to focus on a single system. An accumulation of many and diverse arguments led to selection of the high temperature (450°C) lithium - iron sulphide system. The major problem of this system was known to be the excessively costly boron nitride separator, so attention was focused on reducing the cost of this component; this has now been accomplished on a pilot plant scale. The objective was then to take the laboratory bench scale cell technology to a product technology. The final fully supported phase was to have been the development and construction of a 12-V prototype battery and thermal enclosure for testing. Support for this last phase has been assumed by the Department of Energy, Mines and Resources. The only other high temperature battery competitive with the lithium - iron sulfide was the sodium-sulfur battery which had been extensively researched in several countries for over 20 years.

A capability to test and assess the results of this work was essential and coincided with the minimum requirement that a country relying on foreign technology as extensively as Canada should have a capability for independent and unbiased testing. The nucleus of such a capability, a 10-station cell cycling system, was assembled in-house at the DREO site.

Other battery systems included under this program at a much lower level were the lithium/molybdenum sulfide ambient temperature rechargeable system which makes use of a resource specifically available in Canada, and the aluminum/air battery which, although developed to a lesser degree, has strong potential for giving electric vehicles a range approaching that of conventional gasoline-fueled vehicles. This latter system is of added interest due to the existence of a strong Canadian-based aluminum industry.

Non-hydrocarbon Vehicle Sub-systems

The conventional vehicle of today (land and sea) is typically powered by a heat engine fuelled by a liquid hydrocarbon fuel. For certain limited applications, electric vehicles have also become common (delivery vans in Britain, fork lift trucks, etc.). Efficiency penalties, associated with requiring the energy converter to be sized to provide peak power requirements of the vehicle, have led to various so-called "hybrid" vehicle configurations in which energy storage and conversion technologies are combined optimally. An example is the engine-flywheel combination, in which a relatively small engine in, for example, a city bus, provides the average energy requirements of the bus. Part of the energy is stored from time-to-time in a flywheel, which also stores braking energy. The flywheel is used to provide high power in acceleration and hill climbing. Meanwhile, the engine operates continuously at peak efficiency, resulting in net fuel savings.

Various energy storage and conversion technology developments in Canada and abroad (e.g., advanced batteries, flywheels, advanced transmissions, etc.) indicated a need to assess what additional R&D requirements were needed to ensure timely application to initial Canadian market niches. This led to a wide-ranging study embracing several storage technologies (batteries, mechanical, hydrogen), conversion technologies (electric traction, fuel cells, hydrogen engines), and other sub-system technologies (transmission, controllers, thermal management, etc.) The study, carried out by a Canada - United States industrial team, also assessed several marine, road, off-road, and rail markets. The results of the study cover too many facets to summarize; however, it was expected to provide a valuable planning tool for NRC and other planners in this field, particularly since the study provided a ranking methodology which could be used as a decision-making tool.

The NRC's involvement in flywheel R&D stemmed from a 1977 study by the Urban Transportation Development Centre in Ontario. That study recommended the development of flywheel technology for Canadian applications. Flywheels employing composite materials offered the best performance prospects and appeared to be an area in which there was no dominant foreign lead. Flywheels have a high power density and a high charge-up rate which makes

them well suited to applications such as the stop-start urban bus duty cycle referred to above.

The NRC's flywheel program exploited special expertise at the University of Ottawa and had the aim, in the longer term, of developing a Canadian manufacturing capability in advanced composite-material flywheels. Excellent progress was made in developing materials and design methodology data bases, developing construction techniques and facilities, constructing prototype rotors and hubs, and exposing prototypes to high speed, long duration cycle testing in purpose-designed facilities. The University of Ottawa is currently seeking industrial interest in this flywheel technology.

Thermal Storage

Replacement of oil used for space heating with electricity generated from non-oil primary resources was an available option with existing technology. It was particularly attractive in locations where natural gas was not available, and had the potential for high impact and near term application. Technical difficulties were assessed as low compared with those expected for replacing oil by electricity in other major usage areas such as transportation. However, it was recognized that the increased electrical loads, resulting from direct conversion to electric space heating, would result in increased peak electricity demands. As these peaks were being increasingly supplied by the use of gas turbine generators the net oil displacement would be reduced. The use of storage could allow a utility not only to eliminate new peak demands, but also to reduce existing peaks and allow an increase in the proportion of high efficiency base-load generation.

Centralized storage can be effected by many techniques and has the advantage of being under the direct control of the utility. Alternatively, a dispersed system of small home-based storage units can be employed, which has the added benefit of circumventing potential problems relating to distribution network overloading caused by the increase in electricity demand. This latter option had been in use for many years in Europe, where a time-of-day electric utility rate structure provided the incentive for users to operate thermal storage systems. It was considered highly desirable that Canada should have an indigenous capability to follow this option and a program was commenced to explore the most appropriate heat storage medium for a Canadian application. Both sensible and latent heat storage media were assessed with the near term assessment recommending high temperature sensible heat storage. Apparent advantages of the latent heat storage concepts were found to be unattainable in practice. For example, the claimed ability to have a constant operating temperature meant sacrificing considerable cycling capacity which was unavoidably present as sensible heat. Other major adverse features of the latent heat system related to

difficulties in heat transfer and in corrosion of the containment materials. A small parallel program on sodium sulphate phase change material for solar energy storage was funded for a short period. However, it was realized that solar storage techniques had special requirements and were best considered as an integral part of the solar collection technology. Responsibility for storage associated with solar devices was thereafter passed to the Solar Energy Program.

A decision was made to proceed with a high temperature sensible heat storage system. To cope with the severity of the Canadian climate it was necessary to develop acceptable storage units with greater capacity than those that had been successfully deployed in Europe. To this end a new furnace core material was developed which was based on a specular hematite of Canadian origin. The new brick material was fabricated by a process developed under contract by the Ontario Research Foundation. It had a 40% higher volumetric energy density than the planned American olivine-based cores. Additionally, the furnaces designed and constructed by Chromalox Canada had improved heating element designs, intelligent stand-alone control functions, and improved ease of installation.

At the commencement of the winter season 1983/84 two of the heat storage units were included in an Ontario Hydro load management program and four others were incorporated in on-going field tests with American utilities. The feedback from both utilities and home owners was very positive, to the extent that requests were received that the furnaces be allowed to remain at the field trial locations. The future of this technology in Canada now depends on whether or not a time-of-day electric utility rate structure will be introduced. A recent application by Ontario Hydro was turned down at the Ontario Energy Board. It is possible that a market could be developed in the northern states of the United States where the necessary time-of-day rates are already in effect, in which case, the developed technical capability may be kept intact until such time as conditions are favourable for Canadian use.

Other concepts investigated included closed cycle reversible chemical systems for both storage and transmission of thermal energy. No specific Canadian opportunity could be identified where such systems showed an advantage over accepted conventional methods. Another study explored the potential for a natural-gas fired heat pump for domestic heating. No chemical heat pump system was identified that gave a sufficient performance advantage over the competing condensing gas furnace.

7. EXTERNAL CANADIAN REPORTS

Numerous reports were generated by work performed outside the Hydrogen and Energy Storage program. Many of these reports were policy and planning documents. Those included here had a significant impact on Canadian activities falling within the scope of the federal program on Hydrogen and Energy Storage.

"Discussion Paper on Liquid Fuel Options:" 1980 (34)

A priority setting report which projected liquid fuel costs and compared them with a range of alternatives. The statement on hydrogen included an emphasis on its use as a key input in synfuel manufacture. The concepts about hydrogen costs were subsequently found to be erroneous.

Hydrogen as a Transport Fuel

The use of hydrogen in engines has been demonstrated around the world, and continues to capture the imagination of both scientists and laymen as the perfect or "ultimate" fuel. Hydrogen might eventually assume this auspicious identity, but probably not for many decades to come. There are three practical problems that impede the use of hydrogen as a transport fuel in this century, except possibly in the premium jet fuel market where its exceptionally high energy-to-weight ratio gives it an advantage on aircraft. The first problem with hydrogen is its very high cost of production, whether from natural gas, coal or the electrolysis of water. The major reason for the high cost is poor conversion efficiency. The energy in the hydrogen is much less than the energy in the feedstock. The second problem is distribution and storage. Compared to natural gas, which is already distributed in Canada and which can be stored on vehicles with modest penalties for tank weight and vehicle range, hydrogen is at a substantial disadvantage.

The third problem for hydrogen fuel is that it may have more value as a feedstock for upgrading other energy resources to liquid form than as a fuel itself. Hydrogen is the key energy input in synthetic fuels manufacture and upgrading, and the cost of most new fuel options depends critically upon how the hydrogen is produced and how effectively it is used. Indeed, most of the new fuels discussed in this paper represent ways to store and carry hydrogen energy in chemical combination with carbon, ways that are more energy-efficient than the hydrogen storage technology developed to date.

"Alternative Transportation Fuels for Ontario:" February 1981 (35)

A surprising document with a hard-hitting approach to resolving some of the issues raised by the EMR paper on Liquid Fuel Options. The report included consideration of a full range of alternative vehicle fuel options and took the following position on electricity and hydrogen:

Electricity

The principal objective to 1985 is:

- To promote the use of electric and hybrid vehicles in Ontario.

Major tasks include:

- The establishment of performance and reliability requirements applicable to Ontario's conditions.
- Fleet tests and demonstrations.
- The development of an electric vehicle component industry in Ontario.

Hydrogen

- To investigate the production and utilization of hydrogen for transportation purposes.

Major tasks include:

- Assessment of the technology of hydrogen production and distribution.
- Organization of an industrial development capability.
- Design and construction of components.
- Design, construction, and testing in public transportation.
- Demonstration of hydrogen in transportation.
- Development of hydrogen production and utilization equipment.

"Energy Alternatives:" May 1981 (4)

A much misunderstood report because of the failure to explain the special conditions given to the Parliamentary Committee. These constrained its scope to those energy forms not exploited in Canada to any significant degree at that time. Primarily the Committee was charged with setting aside conventional resources and looking only at alternatives. In the framework of these constraints the Committee's recommendations made interesting reading and admirable sense. With regard to Hydrogen and Energy storage the Committee wrote:

Fuel Cells - Hydrogen

- (33) The Committee recommends that research on fuel cells be funded as part of a commitment to developing a hydrogen economy for Canada. In particular, the development of fuel cells for the transportation sector should be given high priority as their use promises to substitute for transportation fuels, to reduce vehicle exhaust emissions and to develop a market for hydrogen. (p. 159)

Hydrogen

- (38) The Committee recommends that an energy system based upon hydrogen and electricity as the principal energy currencies be adopted by the Government of Canada as a long-term policy objective. (p. 188)
- (39) The committee believes that hydrogen will be an important element of Canada's future energy system and recommends that we begin now to develop the technology and infrastructure for hydrogen production, distribution and use. (p. 188)
- (40) The Committee agrees that the early demonstration of a hydrogen-based urban transportation system is required in Canada and recommends that research into this use of hydrogen be supported with the aim of rapid commercialization. (p. 188)
- (41) The Committee recommends that the Federal Government be prepared to spend up to \$1 billion over the next five years to foster the broad development of a hydrogen-based energy system and to establish Canada as a world leader in hydrogen technology. (p. 189)
- (42) The Committee recommends that a Commission, to be known as Hydrogen Canada, be established to act as the lead agency for hydrogen RD&D and commercialization in Canada. This Commission should report to the proposed Minister of State for Alternative Energy and Conservation. (p. 189)
- (43) The Committee recommends that the proposed Minister of State for Alternative Energy and Conservation begin a review of the progress and accomplishments of Hydrogen Canada after eighteen months, with the review to be completed within six months. A further review should be conducted after the fourth year of the program, with subsequent reviews to follow at five-year intervals. (p. 190)
- (44) The Committee recommends that the results of the periodic reviews of Hydrogen Canada's progress be tabled in Parliament within three months of their completion and, in the event that Parliament is not sitting at the time, the Minister be permitted to make them public. (p. 190)

Air-Aluminum Battery

- (50) The Committee recommends that the Federal Government closely monitor the development of the aluminum-air battery system and that it support commercialization of this power system in Canada. (p. 196)

Electric Vehicle

- (51) The committee recommends that Canada become much more actively involved in electric vehicle research, development and demonstration. This effort should be a systems approach which concentrates not only on propulsion but also on the design and construction of all the components required to produce a completely Canadian electric vehicle. (p. 198)
- (52) The Committee believes that RD&D in this country should concentrate on all-electric vehicles rather than on heat engine/electric hybrids. If hybrid propulsion RD&D is pursued at all, it should be directed towards developing a fuel cell/electric hybrid. This would allow Canada to do research in two areas of non-conventional propulsion

simultaneously, so that at some future date each technology could be profitably exploited on its own. (p. 198)

Hydrogen

- (53) Canada should pursue the use of hydrogen as an alternative aviation fuel and this activity should form part of the overall RD&D efforts of Hydrogen Canada. (p. 200)

The response to the above document from EMR July 1982 (36) was as follows:

Hydrogen

The energy importance of hydrogen may grow quickly. The evidence suggests that the primary role of hydrogen over the foreseeable future will not be as a fuel but in chemical manufacturing and as a vital feedstock in the production of liquid fuels from hydrocarbon resources, particularly oil sands, heavy oil and coal.

Demand for hydrogen in the chemical and petroleum industries is expected to increase by a factor of five by the turn of the century. Electrolytic hydrogen could replace fossil-fuel-derived hydrogen for such purposes by the 1990s. A significant hydrogen production industry can be expected to develop, and the experience gained could be a valuable first step towards the hydrogen economy promoted by the Committee. Significant economic and technical improvements are required before hydrogen could compete with conventional and other alternative fuels.

To investigate production, distribution, storage and utilization aspects of hydrogen, a national hydrogen and electrochemical research and development program has been established by the National Research Council in close collaboration with EMR and other federal departments. This program will be closely linked to expanding research activity in Quebec and Ontario.

Emphasis will be given to advancing the date when electrolytic hydrogen can replace fossil-fuel-derived hydrogen. A full range of technology related to hydrogen production, storage, use (including fuel cells), and batteries will be investigated. Nevertheless, the technological infrastructure required to support the hydrogen economy promoted by the Committee is at a very early stage of development and currently defies any realistic estimate of availability. Current efforts are at the stage of fundamental R&D, and therefore it is difficult to justify support at the level recommended by the Committee in the near future before the opportunities for success become much clearer. The time frame for introducing hydrogen as a fuel is such that Canada can afford to proceed steadily towards this long-term goal. Current government policies are judged sufficient to promote the development of a hydrogen manufacturing industry appropriate to the long-term objective of a hydrogen-based energy system.

Report of the Ontario Hydrogen Energy Task Force: September 1981 (28)

This Task Force conducted a study of depth and scope comparable to that done in Québec and reported subsequently. It made nine recommendations which were all ignored except that the subsequent creation of the Institute for Hydrogen Systems was in part fulfilment of recommendations 3 and 9.

Recommendation 1

The Ontario Government should create an Ontario Hydrogen Development Agency, reporting to the Minister of Energy, to be responsible for:

- (1) the management of an Ontario hydrogen energy research and development program,
- (2) the establishment of projects demonstrating promising utilization technologies for hydrogen,
- (3) the investigation of environmental (including safety) matters directly related to hydrogen in respect of its production, storage distribution and utilization,
- (4) the encouragement of the commercialization of developed hydrogen systems and applications, and
- (5) the availability of a hydrogen supply and its distribution;

and to accomplish the work, whenever feasible, through established resources of the private sector, educational institutions, government agencies and crown corporations.

Recommendation 2

The Ontario Government should establish a policy that permits the procurement of electrical energy - for the provision of hydrogen - at the cost of supply of electricity from hydrogen-committed nuclear capacity when such capacity is in operation.

Recommendation 3

The Ontario Hydrogen Development Agency should establish an Institute for the Development of Hydrogen Systems, under the jurisdiction of the Agency, to plan the Ontario hydrogen energy research, development and demonstration program, and to carry out research and development projects, chosen, after further evaluation by the Institute, from (although not limited to) the hydrogen-oriented aspects of the following areas:

- (1) vehicular power systems; internal combustion engine, gas turbine engine, fuel cell,
- (2) storage and transfer; metal hydride technology, cryogenics, metal embrittlement studies,
- (3) electro-chemistry; electrolyzers, batteries,
- (4) environmental matters; safety, standards.

Recommendation 4

The Ontario Hydrogen Development Agency should appoint a Hydrogen Development Advisory Council, representative of the industrial, academic and governmental communities and of the public, to advise the Agency on program matters, and the Institute on scientific and technical matters.

Recommendation 5

The Ontario Hydrogen Development Agency should include among the projects

of the Institute the investigation and, to the extent found commercially realistic, the development of small-scale decentralized hydrogen energy systems for both domestic and international markets.

Recommendation 6

The Ontario Hydrogen Development Agency should proceed with early-learning field trials designed to gain experience with the handling, distribution and end use of hydrogen and to bring attention to the potential of hydrogen, doing so, where possible, in conjunction with ongoing private and public sector initiatives. Projects that should be given consideration include:

- (1) the conversion of internal combustion engines,
- (2) the conversion of gas turbine engines,
- (3) the incorporation of hydrogen fuel cells in appropriate vehicles with on-board hydrogen storage and supply systems, and
- (4) the utilization of electrolytic hydrogen, in on-going demonstrations, to enhance synthetic liquid fuel (methanol) production from biomass.

Recommendation 7

The Ontario Hydrogen Development Agency, primarily through private sector initiatives, should encourage full investigation and, if proven viable, the utilization of non-fossil-derived hydrogen in oil refinery operations.

Recommendation 8

The Ontario Hydrogen Development Agency should commission at an early date a study to examine the strategies for deployment of electrolysis facilities and related hydrogen distribution systems in Ontario.

Recommendation 9

The Ontario Government should provide funding for the research, development and early-learning field-trial program of the Ontario Hydrogen Development Agency as a minimum after four years, at an annual level of 10 million dollars (1981).

The Role of Hydrogen in the Quebec Economy: December 1981 (37)

This report was the culmination of a massive study undertaken with the support of the Federal and Québec governments and involving Noranda, Air Liquide, Hydro Québec (IREQ), SNC group, Tektrend International, CRIQ, Ecole Polytechnique, and GEIT group. The recommendations as listed below were for a very substantial program. In sharp contrast to the Ontario situation, there has been considerably more success in following up the recommendations.

Recommendations

1. That industry and governments develop the industrial strategy proposed by the Comité québécois de l'hydrogène and take the steps necessary for its implementation.

2. That industry and governments develop the R&D strategy proposed herein by the Comité québécois de l'hydrogène, and take concrete action on pertinent programs so that we may maintain our position in the forefront of electrolysis technology and attain the desired dominant positions in several other areas of the hydrogen industry. The following are examples of programs that might be considered:

- a) The establishment of an industrial-scale water electrolysis demonstration project in Quebec in an appropriate industrial application.

Budget: \$40 million
Decision-making time frame: 1982

The International Energy Agency predicts that the world market for large-scale electrolyzers will reach \$10 billion by the year 2000 and \$47 billion by 2025. The construction of an industrial-scale demonstration project is essential in order to establish the credibility of the local hydrogen industry. Furthermore, we must begin to penetrate the export market as soon as possible in order to maintain our existing advantage in this area, which should be considered the key-stone for long-term success of our hydrogen industry on world markets.

- b) The development and demonstration of a hydrogen-storage facility for temporary electrical surpluses.

Development budget: \$50 million
Decision-making time frame: 1982
Demonstration budget: \$50 million
Deadline: 1986

Inasmuch as a growing number of countries will come to rely on nuclear power for more than just their basic electricity needs, the resulting temporary surpluses will require storage facilities. It is highly likely that hydrogen storage will be used to solve this problem. Dozens of large storage units are expected to be built at a cost of \$2 billion each. At this point, however, it is still difficult to establish a timetable for this scenario.

- c) The development and demonstration of airport facilities required for hydrogen-fueled aircraft, within the framework of an international program for the development of such aircraft.

Development budget: \$50 million
Time frame: 1982-85
Demonstration budget: \$50 million capital investment
Time frame: 1987

One of the main consequences of the advent of hydrogen-powered aircraft will be the installation in every major airport in the world of the infrastructure required to service them. Such infrastructures include liquefaction units capable of producing 1000 tons a day, perhaps the necessary electrolysis plants, and the entire range of auxiliary equipment required to refuel these aircraft and to ensure the control and safety of their operation. The cost of equipping each airport is tentatively estimated at \$2 billion, and it is ex-

pected that in the next thirty years, more than thirty airports will be thus equipped.

- d) As part of an international program for the development of hydrogen-powered aircraft, assuming responsibility for certain aspects of the R&D program, especially with regard to the preliminary studies required for the development of a hydrogen turbine engine.

Development budget: \$25 million
Time frame: 1982-84

Local industry is in a good position to become actively involved in this field. Hydrogen turbines could, over the long term, become a multi-billion dollar market, not counting the benefits to be derived from maintenance programs.

- e) The development and demonstration, in an operational context, of a range of hydrogen-fueled engines for use in off-road commercial vehicles, as well as railway and marine applications.

Budget: \$250 million
Time frame: 1981-86

In today's society, transportation represents approximately 10% of all economic activity. This program is aimed at developing the new, more efficient forms of transportation that will become necessary when liquid hydrocarbon resources are depleted. One can foresee that in certain cases, the demand for hydrogen-powered systems will to a large extent result from political and economic considerations, both domestic and international, well before the depletion of world supplies of liquid hydrocarbons.

- f) Testing of an operational hydrogen pipeline for industrial use.

Budget: \$50 million
Time frame: 1981-86

Replacement of only 1% of the USA's natural gas pipeline by a hydrogen pipeline at a cost of \$250,000 per kilometer would represent a \$1 billion market. Construction of a pilot pipeline is essential in order to incorporate and evaluate the latest technology available in this field, and to establish the credibility of this type of system, of its cost and of its builders.

- g) related research projects on materials, chemical processes, safety aspects and so forth.

Budget: \$65 million
Time frame: 1981-86

More basic research is needed before detailed safety standards can be formulated scientifically. Research is also needed to determine the mechanisms of carbon and biomass liquefaction and to understand the phenomenon of hydrogen embrittlement of metals and the effects of liquid hydrogen on materials in a transitory state. Practical research is required to investigate possibilities relating to non-traditional production and use of hydrogen and its storage underground or by surface adsorption.

3. That industry and governments join together to create the coordinating bodies required for the development and growth of the hydrogen indus-

try, and more specifically, that a council on the hydrogen industry be created. The council should be constituted under the leadership of industry and composed of representatives of industrial firms, universities, research institutes and governments. It would act as the permanent co-ordinator between the various parties during the execution of the aforementioned multidisciplinary program. It would also act as a liaison agency and develop strategy in the field.

4. That industry and governments join together to create technical support agencies, and more specifically, that an electrochemistry research institute be created in Québec as soon as possible to support basic and applied research and local industrial development work in the field of electrolytic hydrogen production and other related fields.

Budget: \$20 million (minimum)
Time frame: 1982-87"

"Alternative Transportation Fuels Utilization Review:" April 1982 (38)

Again a study of very broad scope but one which emphasized the long-term nature of hydrogen applicability as a vehicle fuel. In addition the report stressed the role of regulatory or interventionist action on the market viability of alternative fuels.

Eleven of the thirteen alternative fuels evaluated satisfy, or nearly satisfy, the criteria established for a fuel to be considered commercially available by 1995. Eight of these fuels are evaluated in further detail: methanol and methanol blends; ethanol and ethanol blends; propane; compressed natural gas; and electricity. Although hydrogen does not meet the selection criteria, it has been included for further analysis due to interest in its longer term prospects.

The date of commercial utilization varies among fuels. As shown in Table 1.1 only propane and the alcohol blends will be commercially available as transportation fuels in 1985. All fuels, except hydrogen, could be utilized by 1995. Also shown in the table is the effect of actions which accelerate the introduction of each fuel.

Table 1.1

COMMERCIAL AVAILABILITY OF FUELS

<u>Fuel</u>	<u>Expected Date</u>	<u>Accelerated Date</u>
LPG (Propane, butane)	1985	1980
Methanol blends	1985	1981 - 1983
Ethanol blends	1985	1983 - 1985
Methanol (neat)	1990	1985 - 1987
Ethanol (neat)	1990	1985 - 1987
Electricity	1990	1990
Methane (CNG)	1995	1992 - 1993
Hydrogen	1995+	1995+

The ratings are established on the basis of a consensus of expected trends and the professional judgement of the study team. Many factors may conspire to alter the ratings. A significant (but unexpected) improvement in battery technology, for example, could accelerate electric vehicle utilization. Improvements in storage methods could do the same for CNG. In addition, relative prices of fuels may differ from those assumed. Elimination of the current provincial road tax preference for alternative transportation fuels would affect them all.

A key role to be played by the Ontario Government will be to ensure that the pre-conditions for the commercial availability of alternative fuels are met; be they regulatory, technical or economic. The requirements vary in nature and significance among fuels.

The extent to which government may intervene is, of course, a matter of choice and principle. As one option, government and industry may mutually advance understanding and establish research priorities by engaging in regular conferences and seminars and through the creation of more formal research associations. If the Ontario Government chooses to fund technical research and development, priorities and guidelines will be essential.

Key features of economic incentives programs will be the consistency and the stability which they bring to the market. Current government policy which waives road taxes on alternative fuels appears to have satisfied these objectives; consumers and the automotive and fuels industry have responded in the case of propane. Although successful for propane, a focussed evaluation of each alternative fuel in relation to existing tax policy and other incentives is required to assess the degree to which penetration may be encouraged or accelerated. Limitations to funding such incentives should, of course, be established under different penetration assumptions.

Regulatory aspects are concerned with regulations or standards which governments impose to protect the general public or consumers and other interest groups. In many cases, alternative fuels have features requiring an assessment of the adequacy of existing controls, including: emissions standards; fuel safety; handling procedures; and fuel specification. The utilization of neat methanol, for example, will produce emissions high in aldehydes. Aldehyde emissions are photochemically reactive but unregulated. Little is known of their significance under widespread methanol utilization. In addition, methanol poses a somewhat different hazard than gasoline, both in toxicity and potential for explosion.

Resolving the various regulatory issues concurrently with other research requirements (for example, technical research) rather than sequentially will speed the opportunity of commercial utilization. In addition, establishing standards and the regulatory environment, sets targeted objectives for industry research programs.

A potentially significant role to be played by the Ontario Government is the co-ordination of technical research activities between the automotive and fuels industry. The commercial utilization of most alternative transportation fuels have numerous technical issues which must be resolved. Industry is confident that these issues are not major limiting factors and can be resolved. Their resolution, however, requires co-ordination to ensure engine and fuel developments are compatible.

Additional research is required on vehicle markets for alternative fuels. Detailed profiles of commercial fleet markets is required to accurately match alternative fuels adequacies with potential users. These markets are highly diverse in the type of vehicles used and in their applications. Three commercial markets in particular require focussed attention: commercial use automobiles (including taxis), urban light weight trucks and medium weight trucks. Research requirements include: matching vehicle types to applications, documenting duty cycle and performance characteristics and cataloguing ownership, service and infrastructure characteristics. Focussing on particular applications rather than only vehicle types is the next logical step to be taken to more fully appreciate where the initial penetration of alternative fuels may be targeted.

"Electric Vehicles in Ontario:" July 1982 (39)

The Electric Vehicle Task Force was established under the chairmanship of the Ontario Ministry of Industry and Trade in February 1982. The Task Force also included a cross section of representatives from the private sector, three other Provincial agencies, and three Federal departments.

Its mandate was to assess the technological, market, and economic potential of electric vehicles, identify major opportunities, impediments, costs, and benefits relating to their development, production and use, and identify possible industry-government options to accelerate the commercialization of electric vehicles in Ontario and elsewhere in Canada, with possible export markets in the United States.

The Task Force saw its mandate as acting in support of the relevant stated goals of the Board of Industrial Leadership and Development (BILD). As stated in the document "Building Ontario in the 1980's," these goals (in part) are as follows:

Electricity

... prepare Ontario for the transition to an economic system in the 1980's based increasingly on electrical power and nuclear technology.... The Province's electrical system will be utilized wherever practical, to substitute for oil consumption.... Obtain massive economic benefits from substituting an indigenous energy source for petroleum ... provide greater energy security for Ontario's economic future ... keep Ontario in the forefront of electric power technology.

Transportation

... promote vigorously the development and adoption of transportation systems which conserve energy, reduce oil consumption and build on the demonstrated effectiveness of Ontario's transportation technology.

Electric Vehicles

To help prepare industry for the advent of these vehicles (electric), the Ontario Government will pursue a strategy to encourage the electric vehicle component industry in Ontario.

The Task Force made a strong case for government initiatives in the field which were summarized as follows:

For these reasons, the Task Force is strongly of the opinion that governments and electrical utilities in Canada, and in particular the Ontario and Federal Government, should play a more active role than heretofore in supporting the private sector for the development and commercialization of electric vehicles in this country. For this reason also, the Task Force rejects the option of continuing at the current level of industry/government activities related to electric vehicles.

Making specific reference to batteries the following program was defined:

Focussed development and application engineering to produce engineered and commercial prototypes of up to three of the more promising advanced traction batteries; the more promising candidates from which this selection would be made include zinc-chlorine, zinc-bromine, lithium - metal sulphide, aluminum-air, and sodium-sulphur; discussions would be initiated immediately with companies working on the research and development of such batteries to determine the extent to which government can act as a catalyst in increasing the level of effort and thereby reducing the time required to produce engineered batteries suitable for electric vehicle traction.

This increased level of battery development, to be jointly financed and undertaken by industry and government, could be located largely at a battery development and testing centre, such as the expanded testing centre operated by the Federal Government near Ottawa, and/or it could be conducted at two or three locations where private sector development work is already occurring; a decision on this would be made early in the three year program, based on discussions with private sector firms active in the field.

8. INTERNATIONAL ACTIVITY

Canada became involved in international cooperative programs principally through its participation in International Energy Agency Agreements. In addition, Canada participates in the work of the International Institute for Applied Systems Analysis at Laxenburg-Vienna, Austria. Both activities, particularly the former, have had major impact on the Canadian Hydrogen and Energy Storage program.

The International Energy Agency (IEA) is an autonomous body within the Organization of Economic Cooperation and Development. Canada participated in cooperative programs under the Hydrogen Implementing Agreement signed in October 1977. The other participants included many European countries as well as Japan and the United States. Figure 11 indicates the breakdown of the IEA Hydrogen program into Tasks, and Table 1 shows the program participation and national representation.

The IEA Cooperative Program on Hydrogen was the subject of a presentation made at the 5th World Hydrogen Energy Conference (40).

The current agreements were formulated in very different times when energy crisis philosophies prevailed. Many countries, including Canada, had been searching for ways to redefine individual programs and international

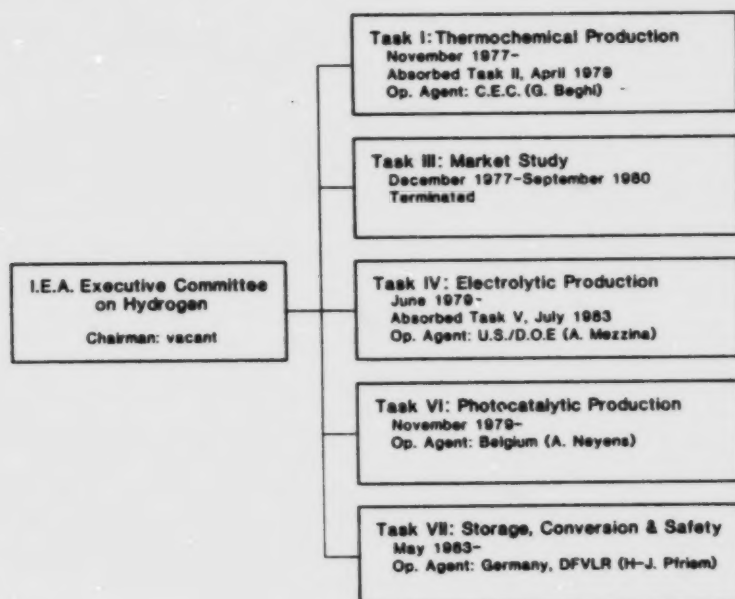


Figure 11. IEA cooperative program on hydrogen (activities).

Table 1. IEA Hydrogen Program (Participation and National Representation)¹

Country	Participant	Participation in Tasks				Executive Committee	
		I	IV	VI	VII	Member	Alternate Member
Belgium	Centre d'étude de l'énergie nucléaire	x	x			F. Altdorfer	H. Vandenborre or M. Reniers
Canada	Department of Energy, Mines and Resources Noranda Mines Ltd. Electrolyser Corp.	x	x	x		J.B. Taylor	A.K. Stuart
CEC	Commission of the European Communities	x	x	x		A. Strub	G. Beghi
Germany	Kernforschungsanlage Jülich	x	x		x	N. Stump	N.A. Struck
Italy	Comitato Nazionale per L'Energia Nucleare	x				S. Ferrari	S. Sabbacini
Japan	The Government of Japan	x	x		x	T. Hirano	H. Irisawa
Sweden	Energy Research Commission				x	B. Finnström	
Switzerland	Département Fédéral de l'Intérieur			x	x	P.E. Zinsli	
United Kingdom	The City University of London	x				A.C. Tseung	K.E. Langley
USA	US Department of Energy	x	x	x	x	J.J. Brogan	M. Gurevich

¹ Operating Agents:

Task I: Thermochemical Production: CEC, acting through the Joint Research Centre. G. Beghi.

Task IV: Electrolytic Production: US DOE, acting through Brookhaven National Laboratory. A. Mezzina.

Task VI: Photocatalytic Production: Katholieke Universiteit Leuven, Belgium. A. Neyens.

Task VII: Storage, Conversion and Safety: Germany acting through DFVLR. H.J. Pfrim.

cooperation. Their deliberations had been summarized in a working paper prepared for the IEA Hydrogen Executive Committee by the then chairman, who was the Canadian representative. The Committee has subsequently endorsed this paper at its meeting in Stockholm, May 1985. Because this paper is not readily accessible, and because it is currently viewed as having major relevance to future activities on both the national and international levels, the summary from it is reproduced below, and the remainder of the paper is reproduced in Appendix B.

SUMMARY

The collective view of numerous international experts on hydrogen energy have been used to define possible future cooperation in R&D programs. Strong arguments are identified in support of the need to continue to explore the possible role of hydrogen in future energy systems. However, the dominant association of hydrogen with new energy systems suggests that a fairly long term view must be taken of the prospects. This implies that the technologies likely to be of significance may not be those of today. This has a very strong influence on the content and scope of R&D programs since they must address the realities of the requirements. A greater emphasis on scientific research content than at present is clearly indicated.

The role of international cooperation is analyzed in terms of the evolutionary flow from invention to technology application. Very significant benefits are identified from cooperation at certain phases of the process. This cooperation must involve the R&D community, governments, potential users and industry. However, cooperation must cross national boundaries because of the magnitude and significance of the energy issue and the global nature of the environmental problem.

The second international activity referred to in the opening paragraph is the International Institute for Applied Systems Analysis (IIASA) which is a non-governmental, multidisciplinary, international research institute founded in 1972 by academies of science and equivalent organizations from 12 nations (including Canada). Its goal is to address common problems resulting from scientific and technological development. The problems of relevance to this program were those of future energy supply and availability. Such problems were addressed in an energy study led by W. Hafele and presented in the IIASA Energy Report "Energy in a Finite World" (41). This publication (reviewed by R. Whitehead (42)), highlights the interdependence of all countries with regard to energy, and provides a basis for speculation on the political implications of future changes in energy sources. The study treated a 50-year period from 1980 to 2030 and used a global model comprised of seven regions with similar energy resources and economic structures. This period was expected to span the transition from non-renewable fossil fuel based systems to sustainable systems based on renewable or non-depletable fuels; however, the study showed that this ideal could only be expected at a much later date. A continual gradual

evolution was visualized from the reliance on cheap oil and natural gas through an extended use of less suitable fossil fuels requiring increasingly costly upgrading to secondary fuels. A major decision was seen to be the choice of using a large fraction of the fossil fuel to provide heat and hydrogen for the chemical upgrading process, or to use exogenous energy sources.

just when demand is moving progressively towards fuels rich in hydrogen — typically methane — an even larger portion of our reserves will be constituted by fuels poor in hydrogen — typically coal and heavy crude oil. In other words hydrogen is in short supply even in our current chemical fuel system. Thus any effort toward developing hydrogen as a possible successor to fossil fuels has the added bonus of more immediately enhancing the usefulness of those fossil fuels that remain.

9. MILESTONES

A number of events in Canada and elsewhere had an impact on shaping and pacing the program. The ones listed here are those which in the judgement of the authors were pivotal in their impact. Armed with this knowledge the reader will be better able to understand the perspectives of those who planned and directed the R&D program.

1976: Cabinet established the Interdepartmental Panel and Office of Energy R&D which remained the main focus of planning and policy until 1985.

1977, June: NRC was assigned program responsibility (Dr. J.B. Taylor appointed as program manager).

1977, July: A meeting was held of the Canadian Working Party on Hydrogen, this was its one and only meeting, in attendance were:

E. M. Jones	Noranda Research Centre
G. Belanger	Hydro Québec Research Institute
N.R. Bharucha	Noranda Research Centre
R.P. Charbonnier	Energy, Mines and Resources, OERD
C. Gardner	Defence Research Establishment Ottawa
M. Hammerli	Atomic Energy of Canada Limited, CRNL
J. Harrison	Ministry of State for Science and Technology
J. Howieson	Energy, Mines and Resources, EPS
G.A. Ingham	Industry, Trade and Commerce, OST
W.F. Johnson	Transport Canada
H.A. Kozłowska	University of Ottawa
R. LeRoy	Noranda Research Centre
D.S. Montgomery	Energy, Mines and Resources
A.K. Stuart	Electrolyser Corp. Ltd.
J. Taggart	Transport Canada
J.B. Taylor	National Research Council
J.H. Walsh	Energy, Mines and Resources, S&T

1977, Oct.: The International Energy Agency Hydrogen Agreement was signed in Paris and the first two tasks were commenced. They were both thermochemical production tasks in which Canada had no participation.

1978, Feb.: The first meeting was held of the Canadian Advisory Committee on Hydrogen.

Attendees were:

E.M. Jones	Noranda Research Centre (Chairman)
A.K. Stuart	Electrolyser Corporation Ltd. (IEA Rep.)
M. Hammerli	Atomic Energy of Canada Limited, CRNL (Secretary)
J. Abouchaar	Transport Canada
G. Belanger	Hydro Québec Research Institute
N.R. Bharucha	Noranda Research Centre
R.P. Charbonnier	Energy, Mines and Resources, OERD
M.A. Chochinov	Manitoba Energy Council
B. Cook	Energy, Mines and Resources, OERD
S. Das Gupta	HSA Reactors Ltd.
C. Gardner	Defense Research Establishment Ottawa
W. Hindle	TransCanada PipeLines
G.A. Ingham	Industry, Trade and Commerce, OST
W.F. Johnson	Transport Canada
H. Kozlowski	University of Ottawa
J.F. Legg	Energy, Mines and Resources, OERD
R.L. LeRoy	Noranda Research Centre
D.J. MacKinnon	Energy, Mines and Resources
E.J. Smith	Industry, Trade and Commerce
J.B. Taylor	National Research Council

- 1978: The Canadian Program of Energy Storage, Conversion and Hydrogen Systems was restructured within Task 1 (conservation) of the OERD.
- 1979, June: Canada (Department of Energy, Mines and Resources) signed the IEA implementing agreement and submitted a program under Tasks IV and V of that agreement. (Dr. M. Hammerli was appointed as Contact Person for Canada for both Tasks).
- 1979, Nov.: Canada participated in the newly formed IEA Task VI on Photocatalytic Production of Hydrogen (Dr. S. Ahmed was appointed as Contact Person for Canada).
- 1979: An International meeting was held in Stuttgart, Germany, on Hydrogen in Air Transportation, with Canada an invited participant.
- 1980, July: An international R&D program for liquid hydrogen fueled aircraft (43), recommended the spending of \$73M over three years on a demonstration program.

- 1980: The "National Energy Program" (2) was released (see Section 2). This emphasized fuel substitution and provided additional funds for energy R&D.
- 1981, Feb.: A study on the establishment of an electrochemical technology centre (27) was completed and recommended procedural, operational, and fiscal details for such a centre, in recognition of the paucity of Canadian activity and expertise in the field of electrochemical technology.
- 1981, May to
- 1981, Sept.: The respective interests of the provinces of Quebec and Ontario were presented in the reports "Elaboration d'une stratégie québécoise de R&D sur l'hydrogène comme vecteur d'énergie" (44) and report of the Ontario Hydrogen Energy Task Force (28),
- 1981, May: Report of the Special Commission on Alternative Energy and Oil Substitution (4), which recommended adopting a long term policy objective of a hydrogen - electricity energy system, that RD&D spending be accelerated and that the technology and infrastructure should be commenced with spending one billion dollars over the subsequent five years. Advanced battery commercialization and increased electric vehicle research were also recommended. This was seen internationally as an impressive Canadian commitment to Hydrogen.
- 1981, June: Energy, Mines and Resources Canada responded (36) to the "Energy Alternatives" report (4) and essentially rejected proposals for accelerated implementation of new energy technologies.
- 1982, Jan.: Hydrogen Industry Council was formed according to recommendations of the Québec report (see section 10).
- 1982, May: The Canadian Hydrogen Energy Association was formed in affiliation with the International Association for Hydrogen Energy.
- 1982, Sept.: An IEA Task VII, Hydrogen Storage Conversion and Safety, was approved (Mr. J.R.B. Murphy was appointed as Contact Person for Canada). Strong Canadian participation was made.
- 1982, Oct.: J.B. Taylor (Canada) became chairman of the International Energy Agency Hydrogen Executive.

- 1983, Jan.: The Institute for Hydrogen Systems (Toronto) was incorporated with funding from the Ontario Government. Capital equipment contributions were subsequently made from NRC.
- 1983, May: The 1st Canadian Hydrogen Workshop was held in Vancouver with the proceedings reported in the International Journal of Hydrogen Energy, V8, No. 4, 1983.
- 1984, July: The 5th World Hydrogen Energy Conference was held in Toronto. This meeting attracted more than 500 participants from 32 countries (13).
- 1984, Nov.: Energy Program funding was cut and the NRC Energy Division terminated. Over a period of 12 months the program responsibility was transferred to the Office of Energy Research and Development, EMR.
- 1985, Sept.: The 2nd Canadian Hydrogen Workshop was held in Halifax, with strong support from the Hydrogen Industry Council. Papers will be published individually in the International Journal of Hydrogen Energy.

10. TECHNICAL ACHIEVEMENTS

Some major technical events have occurred within the scope of the program mandate. The following is a non-exhaustive list of work done in Canada and elsewhere, all of which contributed in some way to shaping the evolution of the Canadian program by defining new targets, generating new data, providing new capabilities, establishing new principles, proving new technologies, etc.

- Advanced unipolar water electrolyzers demonstrated on commercial scale by Noranda/Electrolyser/IREQ (Canada) — very large scale hydrogen production in a cost optimized system.
- Advanced alkaline water electrolyser developed using polyantimonic acid separator (Belgium) — achieved performance and cost targets for alkaline bipolar systems.
- SPE (solid polymer electrolyte) water electrolyser demonstrated on a significant scale by General Electric (U.S.) — defined new performance-/cost target parameters.
- Development and fabrication of novel polymeric membranes resistant to alkali solutions at elevated temperatures (Canada) — separators and new solid polymer electrolytes for advanced electrolyzers and fuel cells.
- Development, fabrication, and testing of a perovskite electrocatalyst for the oxygen evolution reaction (Canada, Belgium) — suitable for advanced alkaline water electrolyzers operating at temperatures up to 200°C.
- Development of production techniques for high quality, stable β " alumina (Canada) — solid electrolyte for fuel cell, battery, and steam electrolyser.
- Demonstration of water splitting using visible light and stable photocatalytic electrodes (Banarjee and Bockris, U.S.) — a dream realised, fuel from sunlight directly but practicability questioned.
- Cristina plant demonstrated at Ispra for thermochemical hydrogen production (EEC) — results do not indicate cost advantages over advanced electrolysis.
- Hydride heat pump (Japan) — precommercial demonstration.

- Hydrogen vehicles running on public roadways (Berlin) — demonstrated safety and capability of hydride storage.
- Use of liquid hydrogen on the space shuttle (NASA U.S.) — technological impact on use and safety of handling liquid hydrogen, also created massive demand for liquid hydrogen.
- Liquid hydrogen aircraft preliminary design completed (U.S.) — cost advantages for long range aircraft.
- Direct injection hydrogen engine (Japan) — overcame preignition problem and permitted excellent full power operation.
- Successful operation of modern diesel engine on ammonia (Canada) — no combustion additives required, self starting, and high efficiency with full power capability.
- Demonstration of automobile running on dissociated methanol (SERI, U.S.) — fueled contentious debate on thermal efficiency gains by such a process, still unresolved.
- 4.5 MW fuel cell tested for utility power generation by United Technologies (U.S.) — led to peak power applications involving hydrogen storage.
- Solid electrolyte fuel cells demonstrated by Westinghouse (U.S.) and Dornier (Germany) — low cost system with no platinum catalysts.
- Boron nitride felt (Canada) — low cost process developed to make battery separators.
- Production prototype Li/FeS battery for electric vehicles (Canada) — high energy battery using boron nitride separator.
- Hybrid and Electric Vehicle Demonstration Act (U.S.) — set target parameters for E.V. and battery developments.
- Design and fabrication of optimized fibre composite flywheels (Canada) — short term high power energy storage with safe operation.
- High capacity thermal storage for electric space heating (Canada) — successful field trials of prototype domestic furnace.

In assessing the program achievements one has to distinguish between those projects which produced tangible hardware and those that did not. Frequently the difference reflects only the state of maturity of the topic in

question. Very few projects actually failed to meet their objectives. Exploratory work is obviously a higher risk than engineering development. However, the former costs much less so the overall economic risk is very low. One should not confine this assessment to the narrow project objectives or to simple cost benefit types of analysis. Much of the program activity was concerned with the development of an intellectual resource base and with establishing effective links and communications. This had the effect of generating a whole new community representing the industrial, government, and academic sectors. The potential loss of this community is perhaps the greatest single effect of the cuts made in November 1984. There are encouraging signs that parts will survive, particularly those which fall within the scope of the Hydrogen Industry Council interests.

Looking specifically at the major hardware projects of the program one sees an across-the-board set of successes. The Li/FeS battery was developed at Hydro-Québec in parallel with the American work at Argonne Laboratories. In 1982 the technology was transferred to a commercial enterprise and in 1984 it was merged with a new low cost separator to produce a very promising product. A great deal separates this product from the multi-million unit market place. At the moment the market place itself is hard to define as only one vehicle is known so far to have operated successfully with a high temperature battery. Battery electric vehicles in general are not penetrating the transportation market at all.

Remaining on the subject of vehicle propulsion one finds considerable similarities with the fibre composite flywheel project. Here again, the Canadian program built on technology from elsewhere but followed a unique approach. Similar questions motivated this work as with the battery work. Basically it was unknown whether an effective device could be made economically, whether it would perform satisfactorily; and whether it would be safe. The project results currently indicate that all these requirements can probably be met. This project has not yet been transferred to a commercial developer and again the market is ill defined. In principle the device has a role to respond to high transient power demands in vehicles equipped with smaller engines or with propulsion systems that have poor power density such as fuel cells. The advent of such vehicles seems now to be pushed to some quite distant future because incentives for their introduction have temporarily disappeared.

The program successes in the field of electrolyser developments has been well publicized. Here again a unique Canadian development is involved. There is considerable advanced electrolyser work around the world but except for Canada, the concentration is on bipolar systems. The Noranda/Electrolyser system is a unipolar design. Its performance characteristics differ from those of other manufacturers. It is specifically designed for

large-scale plants in the hundreds of megawatt size range and under these conditions can produce hydrogen at a cost competitive with other advanced systems. The technology will be demonstrated in a pilot plant to be built at Bécancour, Quebec. The \$25M plant will produce 10 tons of liquid hydrogen per day and will be owned by Air Liquide and Hydro-Québec. This is the second liquid hydrogen plant in Canada. The other owned by Air Products, is at Sarnia, Ontario, and also uses electrolytic hydrogen which in this case is a by-product from a caustic alkali plant nearby.

The next generation electrolyzers will likely operate at higher temperatures and have much higher current loadings to cut capital costs per unit of hydrogen produced. The program has focused attention on materials for these electrolyzers and successfully developed unique new products in both polymeric material and in ceramic material. In all probability both inventions will be picked up commercially.

A much nearer-term and much less glamorous project centered around the application of electricity to domestic space heating. It is obviously possible to substitute electricity for oil directly in this case without new interfacing technology. This is in fact almost unique as an application where such substitution can be effected without a technological interface. However, space heating loads contribute to utility peak demands. Peaking capacity is usually provided at considerable expense and often is oil fired. The use of dispersed thermal storage can displace the space heating load without any effect on the customer. Such storage devices are common in Europe where time-of-day electric rates are general. Canadian domestic thermal loads are very different from those in Europe so a better storage medium is needed. Under the program a superior storage brick was developed and successfully engineered into a furnace unit. These units are on field trials in two American states and in Ontario. The performance has been extremely good.

Many much smaller projects were undertaken. Some were comprised of survey and analysis work which provided inputs to the program planning exercise. In retrospect it is suggested that this work could have been, and should have been, performed within NRC by an appropriate analysis group. It would have been more cost effective than the route chosen. Other hardware projects represented exploratory points of entry into much larger projects. Typical of these were the uses of ammonia or hydrogen as engine fuels. Again the contractors fully met the project objectives and the encouraging results would have led to follow-up work.

This was particularly true in the case of ammonia which critics frequently reject as an alternative fuel. It is, in fact, the only liquid fuel storable at room temperature which can be made without the incorporation of

carbon. Only electricity, water, and air are needed to make ammonia. Its performance as an engine fuel is extremely good — at least as good as propane.

In spite of the glowing report herein on the technological success of the program, not one drop of oil was ever displaced as a result. The authors are not disturbed by this situation for two reasons. In the first place, the work is incomplete and, secondly, the program objective related to R&D in those fields relevant to the National Energy Program targets. An R&D program differs significantly from an application or implementation exercise. The NRC simply lacks the tools and resources to implement anything of this nature, but in this work has clearly demonstrated its ability to create the very necessary wherewithal for others to perform the next step.

11. ORGANIZATIONAL/MANAGEMENT ISSUES

Because this document has been assembled by the past management of the Hydrogen and Energy Storage Program it is clearly not appropriate that this section should be a critique of the program orientation, management, and planning for which they were responsible. However, from the advantageous and privileged position of past program managers it is fitting that their concerns and suggestions should be recorded. What will be looked at here is whether, in retrospect, more effective organization could have been devised, whether different approaches might have produced better results, and whether different perceptions would have changed the program outcome.

The organization of the program was in some measure pre-ordained in that NRC was simply undertaking work on behalf of another department, in this case, EMR. The procedures and priorities of different departments rarely mesh completely so that over-riding structures are established to provide for the required mechanics. Many of the aggravations encountered at the program management level appear to stem from the imposition of a general management scheme without allowance for the special needs of R&D, particularly within the Canadian context. By definition, scientific research deals with uncertainty and discovery. Good management can minimize risk and guide the process of discovery into productive areas, but the required results cannot be forced within a rigidly specified time-frame. The cyclical process defined in Fig. 12 was applied to project approval of funding allocations. It was in the opinion of these authors unnecessarily complex and far too lengthy. A simpler process would have increased the program responsiveness and improved the use of funds. There were occasions when late funding approvals necessitated work compression in order to spend the allocation within the fiscal year. This is not an efficient way of

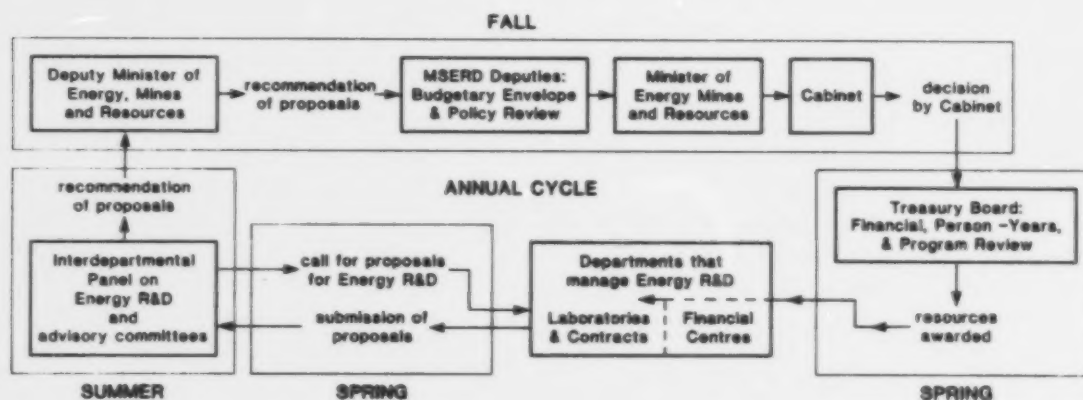


Figure 12. Approval procedure for federal energy R&D.

performing research and development. Lapsing funds are misinterpreted by other agencies.

The aforementioned difficulties were compounded by the contracting-out mechanism within which the NRC was constrained to act. Here again the process was protracted, involving the establishment of a bidders list, issue of a request for proposals, review of responses, contract negotiation, and contract approval. The number of approval levels within the Department of Supply and Services often was so large that progress became a bureaucratic morass. The process frustrated many contractors and become so protracted in one case that 20 months elapsed between the process initiation and the final contract. There is no doubt that better results and significant economies could have been obtained with a more streamlined system.

In contrast to the strong negative reactions to the foregoing procedural matters, the opinions are quite good concerning the perceptions which formed the framework of the program orientation. Whilst recognising the enormity of the problems associated with displacing oil, particularly in transportation uses, the Department of Energy, Mines and Resources recognised the relevance of certain alternative technologies and gave strong support to the R&D program focusing on these technologies. There were extreme political and proponent pressures to emphasize certain hydrogen technologies. These technologies were viewed by EMR and NRC as being of longer term significance and generally program distortions were avoided.

12. FUTURE CHALLENGES AND OPPORTUNITIES

The technologies falling within the scope of the program on Hydrogen and Energy Storage relate to the interfacing of energy sources and demands. The future therefore depends in part on the future of primary energy commodities. In Canada we do not have any shortage of energy. We face only the dilemma of setting priorities for exploitation of resources. However, insofar as utilization technology is concerned, we are able to do little that isolates us from the rest of the world. There the resource availability is different and forcing situations may develop sooner. If we are to attach any credence at all to the historical evolution as analysed by IIASA then we must accept that from the energy point of view we are approaching a transition from systems based on chemical principles, i.e., combustion, to those based on the principles of physics, i.e., nuclear, solar electric, etc. The biggest challenge that we face is in the transition. Only here do we encounter significant problems. Once the change is made it tends to lead to a well-ordered stable situation. We have had a brief fringe encounter with a transition period following the 1973 oil crisis. The experience was not encouraging.

One important aspect of the transition must be the interfacing technology, i.e., that which combines elements of both physics and chemistry to become the discipline called electrochemistry. We ignore this discipline and technology at our peril. Already attempts have been frustrated to encourage more electrochemistry and electrochemical technology in Canada. Efforts must be redoubled because our present electrochemical capability is very limited.

One problem that is not immediately apparent stems from the fact that we cannot predict the technologies of tomorrow. Our needs are obviously for some future time, yet our reference framework is that of today. We cannot predict the forms of energy use or the technologies which will be available at that time. What we do know is that our entry into another age will not be described in some form of step function. Rather, the process will be evolutionary. Presently, we are poorly equipped to engage in this evolution and, since it is not a process leading to commercial gain, the responsibility for action rests squarely on the shoulders of government.

One very encouraging signal from the work already performed is the fact that there is no fundamental impediment to interfacing any future energy form (via electricity as an intermediate) to any conceivable demand. A great deal needs to be done to perfect the technologies and to optimize the hardware to do this but it can be done.

The whole program was triggered by a fear of a pending shortfall in oil supply, which can of course be repeated at any time. Canada is unlikely to

become non-self-sufficient in energy. Undoubtedly, oil supplies will dwindle and we will be faced with the repetition of pressures which we experienced through the seventies. However, there are now very real signs that these pressures will pale by comparison to the pressure which will develop from environmental concerns. Changes in climate associated with carbon dioxide build-up as well as devastation of forests and lakes caused by acid rain will in all probability become crisis issues of the nineties. This will force changes in resource exploitation and in fuel utilization technologies. The technologies addressed under the Hydrogen and Energy Storage program will have dramatically increased relevance at that time.

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APPENDIX B: HYDROGEN: FUTURE COOPERATIVE INTERNATIONAL ACTION

J.B. TAYLOR

Chairman, Hydrogen Executive Committee
International Energy Agency

DECEMBER 1984

INTRODUCTION

There are many factors which influence the setting of national policies on energy research and development. Energy supply and cost, energy mix, and energy uses are just a few of these factors.

They differ enormously from country to country and the result is, not surprisingly, an appreciable difference in national perspectives and policies on energy. Throughout the last decade, the oil supply and pricing issues tended to unify national viewpoints. One outcome of this was the useful cooperative research and development program of tasks performed under various IEA agreements. Partly as a result of this work and partly as a result of the current oil glut, we find ourselves no longer in a crisis situation. National views on energy have matured a great deal. For the energy R & D community in particular, this is indeed an appropriate time to review past action and define future objectives and courses of action.

The community is composed of engineers, scientists, analysts, planners, communicators, etc. who function in a variety of different ways for many disparate purposes. Thus one can identify, for example, those motivated by scientific curiosity; the proponents and enthusiasts; the futurists, etc. From these many viewpoints, it is imperative that some common voice be heard at least insofar as the message reaching governments is concerned. The body of people comprising the Hydrogen Executive Committee of the IEA and their advisors are indeed well positioned to provide such an informed and focussed viewpoint. This document presents a distillation of discussions which have been underway for a year and have involved those persons whose names are appended. It is not in any way to be construed as a document which is endorsed by the individuals and their various national governments. It derives its authority from the collective wisdom and expertise of those who have contributed to the many discussions and exchanges which preceded its preparation.

THE FUTURE ROLE OF HYDROGEN

Hydrogen is already used extensively as an industrial commodity. The energy content of the hydrogen used industrially amounts to between 1 and 50

of the total national energy use. This is a very significant amount of which there is little awareness because it is mostly used captively within the oil industry and as an intermediate in the production of methanol and ammonia. The extent to which these uses will grow is uncertain at present. Ammonia fertilizer production will definitely increase. Also the requirement for hydrogen in the synthetic liquid fuels industry is well appreciated but the future of this particular industry is hard to predict. The real question of significance to the hydrogen R&D community is how much of any additional hydrogen will be derived from traditional sources using existing technologies and how much will involve the development of non-fossil sources and their appropriate new technologies? There is no answer at present to this question, but many people have proposed new hydrogen uses which would result in an order of magnitude increase in the future requirements.

Much has been written about the potential role of hydrogen as a manufactured energy carrier. This concept assigns to hydrogen a role which is complementary to that of electricity. Unlike electricity, hydrogen is a true fuel which can be stored and transported using established techniques. It can be combusted in air and therefore used as a fuel in all heat engines to produce mechanical work. There is no fundamental obstacle to the creation of an energy system based on hydrogen which could displace our current hydrocarbon based system. Hydrogen is a manufactured commodity as are also the hydrocarbon liquid fuels such as gasoline. The relative costs are largely dictated by the primary source costs. Current economics generally favour the hydrocarbons. The principal exceptions to this involve hydroelectric sources applied to hydrogen production by electrolysis. However, it must not be overlooked that storage and transportation for liquid hydrocarbons is substantially simpler than for hydrogen so that system costs bias the choice away from hydrogen.

Many have argued that the **total** system cost is the only relevant criterion and if one includes environmental impact considerations, hydrogen is favoured. The environmentally benign aspects of hydrogen are well established. It is of course necessary that the primary source itself be benign or be controlled at a central facility. This condition can be satisfied much more easily than with dispersed primary conversion which is a feature of the present hydrocarbon based system. A hydrogen energy system does then present favourable opportunities to address environmental issues.

There seems little doubt that the potential of hydrogen is only likely to be fully realised in connection with new energy developments and new energy systems. The conversion of existing systems in some way to

incorporate hydrogen as the energy carrier may occur on a limited scale in certain places but it will not be widespread. **New energy developments** and the development of **new energy systems** will definitely be major pacing factors in the evolution of a hydrogen energy system.

New energy developments for the foreseeable future where hydrogen may be of significance are dominated by the hydraulic potentials in Africa, South America, Greenland, and Canada. Many new hydraulic developments are either underway or contemplated in these areas. Totally new energy systems are eventually expected to emerge based on renewable (photovoltaic, wind, tidal, and nuclear fusion) sources. In all these cases, hydrogen could play a role in the energy delivery step, i.e., the transportation and storage of energy. In fact, if it is this delivery step which is critically important to the system's development, then hydrogen can always contribute. There are common features of all the examples given (remoteness, scale, intermittency, etc.) which suggest that hydrogen could have a vital role to play in such developments.

PRESENT PROBLEMS

The development of a future strategy for hydrogen R&D is constrained by the following realities:

1. There is currently little incentive for fossil fuel replacement (supply and pricing criteria).
2. Existing markets for hydrogen have limited growth potential and the established industry supplying these markets will tend to stay with present sources and present technologies for hydrogen production.
3. New markets for hydrogen are not being developed, use technologies are immature, and there is little awareness of potential commercial opportunities.
4. The hydrogen R&D community, policy makers, potential hydrogen users, and the industrial community do not interface effectively.

Considering only the incentive issue contained in the first statement, it would be understandable if governments were to postpone R&D on all energy alternatives including hydrogen. Such action would be ill-advised because, even ignoring the inevitability of fossil fuel exhaustion, there are many uncontrollable factors which may impact on the nearer term supplies of fossil fuels. Furthermore, environmental issues (including the

carbon dioxide problem) could by the end of the century be a dominant incentive for fossil fuel replacement.

Additionally, it has to be recognized that new incentives for fossil fuel replacement could derive from the technical superiority of an alternative fuel. Historically this has always been the driving forces for change from one fuel type to another. Exhaustion or price have played minor roles in this regard during the initial period of change. Hydrogen offers a very real promise of technical superiority over fossil fuels. This is perhaps best illustrated by the proposed use of hydrogen as an aircraft fuel. In this application, the gravimetric energy density of hydrogen is extremely favourable so that the aircraft size would be reduced whilst the range and performance would be increased. Overall efficiency gains are realizable with all hydrogen fueled engines but these are perhaps overshadowed by the substantial conversion efficiencies already demonstrated by fuel cells. Commercialisation of fuel cells is now very close and all current developments employ hydrogen as the fuel gas although it may often be derived internally from a "carrier" such as methane (natural gas), naphtha, or methanol.

Thus, in spite of the apparent lack of current incentives for fossil fuel replacement there is still an urgent need to examine practical future options which sooner or later will have to be considered as the circumstances change. In the absence of a major curtailment of world oil supplies, a hydrogen energy system must be regarded as a possible long term option and the reasons for this and the pacing factor of new energy developments have already been discussed. However, there appear to be opportunities for the early application of hydrogen technologies on a limited scale. There are also indications of commercial opportunities for the expansion of existing hydrogen applications. There is no real evidence that any of these developments are going to take place without a concerted commitment involving governmental and private sectors of the community. In fact, the task of revising any energy system is enormous and certainly will not be undertaken in isolation by any private organization or even by any one nation. It is inherently a task for governments and requires international cooperation over a long term.

A start has been made under the IEA Hydrogen Agreement. Unless the momentum is maintained, it is unlikely that a viable alternative energy system will be ready when it is needed.

The IEA Executive Committee is responding to the issues that have been identified by redefining R&D needs and by re-emphasizing the ways in which international cooperation can contribute to maintaining and developing the hydrogen option.

PROPOSED RESPONSE

In order to formulate an appropriate response to the situation as defined it is necessary to understand the role of cooperative action and specifically the role of a cooperative R&D program.

The output of any R&D program is defined as comprising "invention" and "data" (see Fig. B-1). It is the combination of these two elements which develops a "capability." In the case of programs under the IEA agreements, it is intended that this "capability" be uniformly distributed among the participants. This is the primary motivation for cooperative action. There is an additional possible output to be derived by the R&D activity usually as a result of testing the invention or analyzing the data.

This is defined in the figure as "information." It should be recognized that inputs to this second process can, and often do, come from sources in addition to those shown in the figure. In fact, it is the expertise built up as a result of the R&D program that allows for the effective assimilation of additional data to optimize the value of the "information" generated. This "information" is of value to policy makers, planners, potential users, and to industry. In conjunction with the established "capability" there may then result a "commitment" leading ultimately to an "application" of the technology. Figure B-1 defines the three major facets of the whole process as "experimentation," followed by "cooperation," and finally "implementation."

The following conclusions can be drawn.

1. There are real benefits to be gained from cooperative action which combines, shares, tests, and analyses the outputs of R&D programs.
2. The translation of such benefits into tangible applications requires that information reach outside the R&D community to policy makers, potential users, and industry. This is usually a weak link in the process but the R&D community must be responsible for ensuring that this step functions effectively.
3. The final application of the technology requires a commitment by governments or industry. This is a matter of individual choice lying outside the scope of present cooperative agreements.

Considering specifically the IEA hydrogen program, it is appropriate to ask whether there are benefits to be gained from further cooperation or whether the implementation stage has been achieved. The situation appears to be



EVOLUTIONARY FLOW FROM R&D TO APPLICATION

Figure B-1. Evolutionary flow from R&D to application.

that in some areas we are approaching this latter situation. There is a definite capability in regard to the non-fossil production of hydrogen which is well developed as a commercial product in the case of electrolysis and less developed in the case of thermochemical. However, the process of testing and analysis which will bring together the various communities is incomplete.

In other areas, data and inventions are still being generated and the "capability" does not yet exist. Thus, in spite of what may have been written by zealous hydrogen energy proponents we are dealing with an immature technology. Attempts to define and quantify this technology have largely been based on rudimentary data. The indications from such work are encouraging. It would be prudent to adopt the view at this time that hydrogen is not a "quick-fix" for any energy problem. It should be seen as presenting an opportunity for the eventual creation of a better energy system. This is not feasible right now on any significant scale for economic and technical reasons. It therefore presents us and succeeding generations with a challenge. The proper response at this time to the challenge is a carefully planned research and development program in which there is an essential role for international cooperation.

RESEARCH AND DEVELOPMENT NEEDS

The understanding of current problems and the formulation of general

responses lead to the recognition of certain specific actions which would be effective in the following ways:

- A. advancing the collective capability of IEA members
- B. maximizing the benefits in the light of constrained funding
- C. providing detailed and updated information to governments and to the community at large

These actions include, but, are not limited to the following specific co-operative R&D program undertakings. These are either new (as in 2 and 3) or represent a considerable departure in scope and emphasis from existing work under the IEA Hydrogen Agreement (as in 1).

1. **Identification of new technical goals and setting new R&D objectives to ensure that the program scope fully reflects the reality of the potential requirements**

The program scope can include a range of activities such as data acquisition, refinement, and hardware development. However, bearing in mind the anticipated time for the possible use of hydrogen energy on a significant scale, it must be emphasized that today's technology may play very little part in the process. Instead, technologies which are yet to be developed may be of the greatest importance. These future technologies will evolve from today's inventions. It is therefore imperative that the program content reflect this reality and recognize the extremely important role to be played by scientific research. The value of scientific research in the field of photoelectrolysis, for example, may be readily apparent but what is perhaps less obvious is that a fundamental research effort is equally valid for all other aspects of hydrogen energy.

2. **Evaluation and testing of existing technologies and equipment**

Newly developed technologies which are considered potentially viable should be subject to detailed evaluation and testing. The purpose of this is to generate a common information base which is presently lacking. Such a data base may be urgently needed and would serve not only to define the degree of readiness in case of accelerated need, but would have considerable value in support of early limited applications of hydrogen technologies. The benefits would not only be the stimulation given to the R&D community, but would include the value of the "information" (as already defined in Fig. 3-1) to those who plan R&D, make energy policy decisions, or make public and private investment commitments.

3. Identify early opportunities for hydrogen applications

This can be achieved by a detailed technical and economic assessment using common data and common procedures. In so doing, it will involve the R&D community, governments, potential users, and industry. The mechanism should provide a framework for a continuing process of iteration and refinement. The output from this activity would essentially standardize procedures for handling results from the testing and evaluation programs of item 2. It would tend to emphasize a fairly early time frame for implementation and would in so doing be stressing commercial opportunities.

It must be recognized that the identification of opportunities for hydrogen application can vary from country to country depending on factors which are external to the technology under consideration. It is possible to establish a common technical data base, as well as methodology and procedures, for conducting technoeconomic assessments; however, the implementation of the data base and methodology is a matter for the individual participants. Such differences as exist in the countries' domestic resource base, energy use patterns, commercial/industrial base, complexity of its energy infrastructures, etc., will call for differing criteria when evaluating the viability of a given application.

APPENDIX C: REPORTS LISTING

The following is a listing of reports resulting from work contracted by the Hydrogen and Energy Storage Program. Contractors are ordered alphabetically and their reports sub-listed chronologically. This is followed by a list of publications authored by H&ES program personnel and final contractor reports outstanding at the time of writing.

Acres Consulting Services Ltd.

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- Volume I - Main Text
- Volume II - Appendices A to D

"Canadian Chemical Heat Pump Application for Space Heating," Final Report, February 1982.

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A.E. Steck, "Development and Characterization of Aromatic Ionomer Membranes," IEA Hydrogen Task IV Workshop, July 1985.

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"Assessment of Hydrogen Bulk Storage in Canada," Phase I Report, August 1983.

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Highquest Engineering Inc., "Thermal Energy Conversion Cycles Exploiting Unique Features of Hydrogen," March 1985.

B.C. Hydro, "The Hydrogen Energy Park Concept," March 1985.

B.C. Hydro, "The Hydrogen Energy Economy Bamfield B.C.," March 1985.

Jarvis Clark Company, "Potential New Uses of Hydrogen in Off-Road and Mining Equipment," July 1985.

Urban Transportation Development Corporation, Support documentation to above.

Canocean, "Marine Uses of Hydrogen," January 1985.

Escher Technology Associates, "Hydrogen as an Aircraft Fuel," November 1984.

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Vol. VI, Flywheel Implementation Plan

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A.E. Steck, "Preparation, Characterization and Development of Aromatic Ionomer Membranes for Hydrogen Production," November 1985.

B.C. Hydro

"Fuel Cell Power Plant Testing Program"

Daychem Laboratories Inc.

"Preparation, Characterization and Development of Aromatic Ionomer Membranes for Hydrogen Production"

Electrofuel Manufacturing Co.

"Boron Nitride Battery Separator Phase III: Pilot Plant Development"
"Development of Molten Salt Secondary Battery — Bicell Fabrication — Phase I and II"

Institute for Hydrogen Systems

"Vibration Testing of an On-board Liquid Hydrogen Dewar"

McGill University

"A Study of the Mechanical properties of Selected Aromatic Ionomers for use as Membrane Materials in Advanced Alkaline Electrolyzers — Phase IV"

"Preparation Characterization and Development of Aromatic Ionomer Membranes for Hydrogen Production", Final Report.

Noranda Mines Limited

"Technology Development of Electrolytic Production of Hydrogen"

Ontario Research Foundation

"Development and Assessment of Glass Microcapsules for Hydrogen Storage, Phase III"

Queen's University

"The Selection, Preparation and Characterization of Ceramic Hydrogen Ion Conductors" — Phase VI, Final Report

University of Ottawa

"Construction and Extended Testing of Final Rotor Designs, and Final Documentation of Flywheel Program"

University of Toronto

"Injection Hydrogen Fueled Diesel Engines with Ignition Assist"

York University

"The Development of Multi-Electron Electrocatalysts"

APPENDIX D: MAJOR PARTICIPANTS

The following list of Major participants in the Hydrogen and Energy Storage Program is presented in alphabetical order of the organization under the subprogram headings used in part 6, Program Content.

HYDROGEN PRODUCTION ELECTROLYSIS

ORGANIZATION	CONTACT NAME PHONE NUMBER	SUBJECT
Atlantic Industrial Research Institute	Mr. G.P. Wilson 902-429-8300 Ext. 145	Electrocatalysts
Ballard Technologies Corp.	Dr. K.P. Prater 604-986-4104	Membranes and Separators for Advanced Electrolyzers
Carleton University	Mr. M.D. Guiver 613-993-0198	Membranes for Advanced Electrolyzers
Daychem Laboratories Inc.	Dr. F.W. Harris Akron, U.S.A. 216-375-7511	Membranes and Separators for Advanced Electrolyzers
Ecoplastics Ltd.	Dr. J.E. Guillet Dr. M. Heskins 416-499-3060	Separators for Advanced Electrolyzers
Electrolyser Corp.	Mr. A.K. Stuart 416-621-9410	Sub-contractor to Noranda Mines Ltd.
Gould Manufacturing of Canada Limited	Dr. K.V.N. Rao Dr. R. Swaminathan Dr. R. Gopal 416-871-5600	Electrocatalysts for Water Electrolysis
Life Systems Incorporated	Dr. F.H. Schubert Cleveland, U.S.A. 216-464-3291	Small Scale Electrolyzers

HYDROGEN PRODUCTION ELECTROLYSIS (Continued)

ORGANIZATION	CONTACT NAME PHONE NUMBER	SUBJECT
McGill University	Prof. A. Eisenberg 514-392-4444	Membranes and Separators for Advanced Electrolyzers
McMaster University	Dr. D.A. Thompson Prof. W.W. Smeltzer 416-525-9140 Ext. 4563 Dr. P.S. Nicholson 416-525-9140 Ext. 4977	Electrocatalysts for Water Electrolyzers Sub-contractor to Queen's University
Noranda Mines Limited	Dr. R.L. LeRoy 514-697-6640	Water Electrolyzers
Queen's University	Prof. M. Sayer 613-547-6176	Ceramics for High Temperature Electrolyzers
Raylo Chemicals Ltd.	Dr. R. Vukov Dr. J. Prescott 403-469-7601	Separators for Advanced Electrolyzers
Sheritt Gordon Mines Limited	Mr. R.W. Fraser 403-998-6911	Sub-contractor to Noranda Mines Limited
University of Calgary	Prof. H.L. Yeager Dr. A.E. Steck 403-284-5370	Ionic Properties of Membranes for Advanced Electrolyzers
University of Toronto	Prof. C.A. Ward 416-987-3050	Bubble Formation in Electrolyzers
York University	Dr. A.B.P. Lever 416-667-2309	Electrocatalysts for Advanced Electrolyzers

THERMAL

ORGANIZATION	CONTACT NAME PHONE NUMBER	SUBJECT
Energy Research Corporation	Dr. E. Bilgen 514-344-4711	Thermochemical Hydrogen Production

HYDROGEN UTILIZATION SYSTEMS ANALYSIS

B.C. Hydro	Mr. L.A.J. Roosdahl 604-663-4243	Sub-contractor to Chemetics, see below
CanOcean Resources Limited	Mr. C. Ostick	Sub-contractor to Chemetics, see below
Costain Petrocarbon Limited	Mr. J. Mills 403-252-9711	Sub-contractor to Chemetics, see below
Chemetics International Co.	Mr. R.E. Knowlton	New Uses for Hydrogen
Highquest Engineering Inc.	Dr. B.G. Keefer 604-687-2859	Sub-contractor to Chemetics, see above
Hydrogen Industry Council	Mr. R.D. Champagne 514-288-5139	Program Planning
Jarvis Clark	Mr. P.H. French 416-632-4940	Sub-contractor to Chemetics, see above
Urban Transportation Development Corp.	Mr. D. Ference 613-389-9978	Sub-contractor to Chemetics, see above

STORAGE

CANATOM Inc.	Mr. L.A. Phillips 514-879-4511	Hydrogen Bulk Storage
Ontario Research Foundation	Dr. S. Johar 416-822-4111	Hydrogen Storage

STORAGE (Continued)

ORGANIZATION	CONTACT NAME PHONE NUMBER	SUBJECT
University of Toronto	Dr. F.D. Manchester 416-978-2978	Hydrides

SAFETY

Atomic Energy of Canada Limited	Dr. R. Dutton 204-853-2311	Sub-contractor to Canatom, see below
	Dr. H. Tamm	Hydrogen Safety Committee Member
B.C. Hydro and Power Authority	Mr. R.M. Caines 604-663-4417	Hydrogen Safety Committee Member
Canatom Inc.	Mr. J. Riley 416-366-9421	Hydrogen Embrittlement
Chemetics International Limited	Mr. R.E. Knowlton 604-734-1200	Hydrogen Safety
		Hydrogen Safety Committee Executive Secretary
Hydrogen Industry Council	Dr. D.R. Hay 514-288-5139	Hydrogen Safety Committee Chairman
Institute for Hydrogen Systems	Mr. G. Hayward 416-828-7700	Liquid Hydrogen Tanks
		Hydrogen Safety Committee Member Sub-contractors to Canatom, see above
Ontario Research Foundation	Dr. J. Lo 416-822-4111	Sub-contractor to Canatom, see above

SAFETY (Continued)

ORGANIZATION	CONTACT NAME PHONE NUMBER	SUBJECT
Union Carbide Canada	Mr. D.W. Kirkwood 416-488-1444	Hydrogen Safety Committee Member

FUEL CELLS

B.C. Research	Dr. V.A. Mode 604-224-4331	Sub-contractor to B.C. Hydro, above
B.C. Hydro	Dr. H.M. Ellis Dr. M. Papic 604-591-0200	40KW Fuel Cell Program
DSMA Atcon Limited	Mr. A.P. Bullock 416-239-3011	Planning for Fuel Cell Testing
HSA Reactors Limited	Mr. Fleet 416-789-7593	Sub-contractor to DSMA Atcon Limited, see above
Institute for Hydrogen Systems	Dr. D.S. Scott 416-828-7700	Federal Contribution Agreement
Science Applications International Corporation	Mr. W.C. Racine LaJolla, Ca. USA	40KW Fuel Cell Program
United Technologies	Mr. A.P. Meyer South Windsor, CONN U.S.A. 203-727-2214	40KW Fuel Cell Program

ENGINES

Associated Kellogg Limited Toronto	Mr. L. Blake 416-252-5311	Small Ammonia Systems
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ENGINES (Continued)

ORGANIZATION	CONTACT NAME PHONE NUMBER	SUBJECT
Chemetics International Limited	Mr. R.E. Knowlton 604-734-1200	Ammonia Safety
Engelhard Industries of New Jersey, U.S.A.	Mr. A. Stawsky 201-321-5234	Methanol Decomposition for Vehicle Fuel
Manitoba Research Council Winnipeg	Mr. D.E. Mathers 204-945-6122	Ammonia-Fueled Engine
Midwest Detroit Diesel Limited, Winnipeg	Mr. B. Norrie 204-452-8244	Sub-contractor to Manitoba Research Council see above
Ontario Research Foundation	Dr. A. Lawson 416-822-4111	Methanol Decomposition for Vehicle Fuel Planning for SERI Program see below
Pratt and Whitney Canada Limited	Mr. H.C. Eatock 514-677-9411	Hydrogen Combustion in Gas Turbines
Solar Energy Research Institute, Denver, Colorado	Dr. H. Chum 303-231-7249	Dissociated Methanol as a Vehicle Fuel
University of Toronto	Dr. J.S. Wallace 416-978-3043	Hydrogen Engines

ENERGY STORAGE ADVANCED BATTERIES

Alcan International Limited	Dr.N.P. Fitzpatrick 613-549-4500	Al/Air Battery
Blue Mountain Pottery Limited	Mr. R.L. Miller 705-445-3671	Separators for the Li/FeS Cell

ENERGY STORAGE ADVANCED BATTERIES (Continued)

ORGANIZATION	CONTACT NAME PHONE NUMBER	SUBJECT
Electrofuel Manufacturing Company	Dr. S. Das Gupta 416-533-7368	Li/FeS Batteries
IREQ, Hydro-Québec	Dr. G. Bélanger 514-652-8231	Li/FeS Cells
M.K. Murthy Associates	Dr. M.K. Murthy 416-920-6188	Ceramics Consultant for High Energy Batteries
Ontario Research Foundation	Dr. S. Johar 416-822-4111	Sub-contractor to Blue Mountain, see above

VEHICLE SUBSYSTEMS

Davis Engineering Ottawa	Mr. R. Davis 613-748-5500	Vehicle Subsystems
University of Ottawa	Dr. R. Flanagan 613-231-4093 613-231-5700	Flywheel Development

THERMAL STORAGE

Acres Consulting Services Limited	Mr. I. McCaig 416-354-3839	Chemical Heat Pumps
American Electric Power Service Corp. Ohio, U.S.A.	Mr. W. Coleman	Field Trials for Heat Storage Furnace
Chromalox Canada Limited	Mr. L.E. Toffolo 416-677-4614	Heat Storage Furnace for Electric Space Heating
Minnesota United Power Minn. U.S.A.	Mr. V. Lehronger 612-441-3121	Field Trials for Heat Storage Furnace

THERMAL STORAGE (Continued)

ORGANIZATION	CONTACT NAME PHONE NUMBER	SUBJECT
Ontario Hydro	Mr. J.R. McRae 416-592-3780	Field Trials for Heat Storage Furnace
Ontario Research Foundation	Dr. S. Johar	Heat Storage Furnace for Electric Space Heating

PROGRAM PLANNING

DND/Defense Research Establishment Ottawa	Dr. W.A. Adams 613-998-2347	Program Planning
EMR/CANMET	Dr. S.M. Ahmed 613-995-4707	Program Planning
Escher Technology Associates	W.J.D. Escher	Program Planning
Hydro-Québec (IREQ)	Dr. G. Bélanger 514-652-8231	Program Planning
NRC - Chemistry Division	Dr. J.J. Murray 613-993-2506	Program Planning
Ontario Hydro	Mr. A.G. Barnstaple 416-592-5209	Program Planning
Ontario Ministry of Energy	Dr. R. Higgin 416-065-4366	Program Planning
Quebec Government	Mr. G. Délage 418-643-1283	Program Planning